

NATIONAL INVENTORY REPORT 1990–2020: GREENHOUSE GAS SOURCES AND SINKS IN CANADA

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LIST OF COMMON ABBREVIATIONS AND UNITS

Abbreviations

CAC	criteria air contaminant
CANSIM	Statistics Canada's key socioeconomic database
CEPA 1999	<i>Canadian Environmental Protection Act, 1999</i>
CESI	Canadian Environmental Sustainability Indicators
CFC	chlorofluorocarbon
CFS	Canadian Forest Service
DOC	dissolved organic carbon
ECCC	Environment and Climate Change Canada
EF	emission factor
FRD	facility reported data
GDP	gross domestic product
GHG	greenhouse gas
GHGRP	Greenhouse Gas Reporting Program
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HWP	harvested wood products
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
LTO	landing and takeoff
LULUCF	Land Use, Land-Use Change and Forestry
MSW	municipal solid waste
N/A	not available
NDC	nationally determined contribution
NIR	National Inventory Report
NMVOC	non-methane volatile organic compound
NPRI	National Pollutant Release Inventory
ODS	ozone-depleting substance
OECD	Organisation for Economic Co-operation and Development
PFC	perfluorocarbon
POP	persistent organic pollutant
QA	quality assurance
QC	quality control

RESD	<i>Report on Energy Supply and Demand in Canada</i>
TAN	total ammoniacal nitrogen
UOG	upstream oil and gas
VKT	vehicle kilometres traveled
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change

Chemical Formulas

Al	aluminium
CaCO ₃	calcium carbonate; limestone
CaMg(CO ₃) ₂	dolomite
CaO	lime; quicklime; calcined limestone
CF ₄	carbon tetrafluoride
C ₂ F ₆	carbon hexafluoride
CH ₃ OH	methanol
CH ₄	methane
C ₂ H ₆	ethane
C ₃ H ₈	propane
C ₄ H ₁₀	butane
C ₂ H ₄	ethylene
C ₆ H ₆	benzene
CO	carbon monoxide
CO ₂	carbon dioxide
CO ₂ eq	carbon dioxide equivalent
H ₂	hydrogen
H ₂ O	water
H ₂ S	hydrogen sulphide
HNO ₃	nitric acid
Mg	magnesium
MgCO ₃	magnesite; magnesium carbonate
MgO	magnesia; dolomitic lime
N	nitrogen
N ₂	nitrogen gas
Na ₂ CO ₃	sodium carbonate; soda ash
NF ₃	nitrogen trifluoride
NH ₃	ammonia
NH ₄ ⁺	ammonium
NH ₄ NO ₃	ammonium nitrate
N ₂ O	nitrous oxide
N ₂ O-N	nitrous oxide emissions represented in terms of nitrogen
NO	nitric oxide

NO ₂	nitrogen dioxide
NO ₃ ⁻	nitrate
NO _x	nitrogen oxides
O ₂	oxygen
SF ₆	sulphur hexafluoride
SiC	silicon carbide
SO ₂	sulphur dioxide
SO _x	sulphur oxides

Notation Keys

IE	included elsewhere
NA	not applicable
NE	not estimated
NO	not occurring

Units

g	gram
Gg	gigagram
Gt	gigatonne
ha	hectare
kg	kilogram
kha	kilo hectare
km	kilometre
kt	kilotonne
kWh	kilowatt-hour
m	metre
Mg	megagram
Mha	million hectares
mm	millimetre
ML	megalitre
Mt	megatonne
MW	megawatt
PJ	petajoule
TJ	terajoule
t	tonne
TWh	terrawatt-hour

ANNEX 1

KEY CATEGORIES

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A1.1. Key Categories – Methodology

This annex presents the use of an Intergovernmental Panel on Climate Change (IPCC) Tier 1 key category analysis and results for Canada's inventory submission. The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) recommend as good practice the identification of key categories of emissions and removals. The intent is to help inventory agencies prioritize their efforts to improve overall estimates. A key category is defined as “one that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of greenhouse gases in terms of the absolute level of emissions and removals, the trend in emissions and removals, or uncertainty in emissions and removals” (IPCC, 2006); this term is used in reference to both source and sink categories.

Good practice first requires that inventories be disaggregated into categories from which key sources and sinks may be identified. Source and sink categories are defined according to the following guidelines:

- IPCC categories should be used with emissions expressed in carbon dioxide (CO₂) equivalent units according to standard global warming potentials (GWP_s).
- A category should be identified for each gas emitted or removed, since the methods, emission factors, and related uncertainties differ for each gas.
- Categories that use the same emission factors based on common assumptions should be aggregated before analysis.

The IPCC Tier 1 quantitative approach is used to identify key categories from two perspectives: their contribution to the overall emissions and their contribution to the emission trend. The level assessment analyzes the emission contribution that each category makes to the national total (with and without Land Use, Land-Use Change and Forestry [LULUCF]). The trend assessment uses each category's relative contribution to the overall emissions, but assigns greater weight to the categories whose relative trend departs from the overall trend (with and without LULUCF). In this assessment, trends are calculated as the absolute changes between the base and most recent inventory years.

The percent contributions to both levels and trends in emissions are calculated and sorted from greatest to least. A cumulative total is calculated for both approaches. A cumulative contribution threshold of 95% for both level and trend assessments is a reasonable approximation of 90% uncertainty for the Tier 1 method of determining key categories (IPCC, 2006). This threshold has therefore been used in this analysis to define an upper boundary for key category identification. Hence, when source and sink contributions are sorted in decreasing order of importance, those largest ones that together contribute to 95% of the cumulative total are considered quantitatively to be key.

Level Assessment

Level contribution of each source or sink is calculated according to Equation A1–1, which follows IPCC (2006):

Equation A1–1 for source and sink category level assessment:

$$L_{x,t} = \frac{|E_{x,t}|}{\sum_y |E_{y,t}|}$$

- $L_{x,t}$ = level assessment for source or sink x in latest inventory year (year t)
 $|E_{x,t}|$ = the absolute value of emission or removal estimate of source or sink category x in year t
 $\sum_y |E_{y,t}|$ = total contribution, which is the sum of the absolute values of emissions and removals in year t calculated using the aggregation level chosen by the country for key category analysis; because both emissions and removals are entered with positive sign, the total contribution/level can be larger than a country's total emissions less removals

Trend Assessment

The trend contribution of each source and sink is calculated according to Equation A1–2 and Equation A1–3 following IPCC (2006). Note that the use of Equation A1–3 only applies to source and sink categories where there are zero emissions in the base year.

Equation A1–2 for source and sink category trend assessment:

$$T_{x,t} = L_{x,0} \cdot \left| \left[\frac{(E_{x,t} - E_{x,0})}{|E_{x,0}|} \right] - \left[\frac{(\sum_y E_{y,t} - \sum_y E_{y,0})}{|\sum_y E_{y,0}|} \right] \right|$$

- $T_{x,t}$ = trend assessment of source or sink category x in year t as compared to the base year (year 0)
 $L_{x,0}$ = the level assessment for source or sink category x in year 0 (derived in Equation A1–1)
 $E_{x,t}$ and $E_{x,0}$ = real values of estimates of source or sink category x in years t and 0, respectively
 $\sum_y E_{y,t}$ and $\sum_y E_{y,0}$ = total inventory estimates in years t and 0, respectively

Equation A1–3 for source and sink category trend assessment with zero base year emissions:

$$T_{x,t} = \left| \frac{E_{x,t}}{\sum_y |E_{y,0}|} \right|$$

- $T_{x,t}$ = trend assessment of source or sink category x in year t as compared to the base year (year 0)
 $E_{x,t}$ = real values of estimates of source or sink category x in year t
 $\sum_y |E_{y,0}|$ = total inventory estimates in year 0

The overall purpose of identifying key categories is the institution of best practices in greenhouse gas inventory development. The appropriate aggregation of categories is crucial to reflect not only actual sources and sinks but also identical estimation procedures. In this analysis, sectors and major categories such as Fuel Combustion, Fugitive Emissions, Industrial Processes and Product Use (IPPU), Agriculture and Waste are in keeping with the common reporting format (CRF). Thus, while the UNFCCC CRF categories provide a basis for identifying sources and sinks, some aggregation of these sources and sinks has been made for the purpose of key category analysis. In general, the aggregation of categories has been performed when estimates are based on common emission factors and activity data. An exhaustive list of the aggregated categories as well as explanations regarding the rationale for category aggregation is presented in Table A1–1.

Table A1–1 Aggregation of IPCC Categories

Source Table	Aggregated IPCC Category	Categories Included in the Aggregated IPCC Categories	Rationale for Aggregation
1-A-1	Stationary Fuel Combustion – Energy Industries	Public Electricity and Heat Production Petroleum Refining Industries Manufacture of Solid Fuels and Other Energy Industries	Table 4.1, Volume 1: General Guidance and Reporting of the 2006 IPCC Guidelines suggest aggregation to the 1-A-1 level for a Tier 1 approach (IPCC, 2006).
1-A-2	Stationary Fuel Combustion – Manufacturing Industries and Construction	Iron and Steel Non-Ferrous Metals Chemical Pulp, Paper and Print Non-Metallic Minerals Other	Table 4.1, Volume 1: General Guidance and Reporting of the 2006 IPCC Guidelines suggest aggregation to the 1-A-2 level for a Tier 1 approach (IPCC, 2006).
1-A-3-b	Fuel Combustion – Road Transportation	Heavy-Duty Diesel Vehicles Heavy-Duty Gasoline Vehicles Light-Duty Diesel Trucks Light-Duty Diesel Vehicles Light-Duty Gasoline Trucks Light-Duty Gasoline Vehicles Motorcycles Natural Gas Vehicles Propane Vehicles Urban Bus	Table 4.1 in Volume 1 : General Guidance and Reporting of the 2006 IPCC Guidelines suggest that road transportation be aggregated to the 1-A-3-b level for a Tier 1 approach (IPCC, 2006).
1-A-4	Stationary Fuel Combustion – Other Sectors	Commercial and Institutional Residential Agriculture and Forestry, and Fisheries	Table 4.1, Volume 1: General Guidance and Reporting of the 2006 IPCC Guidelines suggest aggregation to the 1-A-4 level for a Tier 1 approach (IPCC, 2006).
1-B-2-(a+c)	Fugitive Emissions – Oil	Oil Venting – Oil Flaring – Oil Venting – Combined (split with 1-B-2-(b+c)) Flaring – Combined (split with 1-B-2-(b+c))	Table 4.1, Volume 1: General Guidance and Reporting of the 2006 IPCC Guidelines suggest aggregation to the 1-B-2-a level for a Tier 1 approach (IPCC, 2006).
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	Natural Gas Venting – Natural Gas Flaring – Natural Gas Venting – Combined (split with 1-B-2-(a+c)) Flaring – Combined (split with 1-B-2-(a+c))	Table 4.1, Volume 1: General Guidance and Reporting of the 2006 IPCC Guidelines suggest aggregation to the 1-B-2-b level for a Tier 1 approach (IPCC, 2006).

Table A1-1 Aggregation of IPCC Categories (cont'd)

Source Table	Aggregated IPCC Category	Categories Included in the Aggregated IPCC Categories	Rationale for Aggregation
2-B-8	Petrochemical and Carbon Black Production	Carbide Production (reported in 2B5 in the CRF, but with 2B8 for the purpose of key category analysis) Methanol Production Ethylene Production Ethylene Dichloride Production Carbon Black Production Styrene Production Ethylene Oxide Production Other (Other Uses of Urea) (reported in 2B10 in the CRF, but with 2B8 for the purpose of key category analysis)	For simplicity and data confidentiality reasons, these categories are included in "Petrochemical and Carbon Black Production" for the purpose of key category analysis. Efforts will be made to disaggregate these categories in future inventories. See below for comments related to CO ₂ emissions from certain petrochemical categories.
2-C-1	Iron and Steel Production	Steel Production Pig Iron Production Metal Industry – Ferroalloys Production	Disaggregation of the reductant portion of steel production (i.e. metallurgical coke) is not available and therefore emissions have to be reported under category 2.C.1.b Pig Iron production. CO ₂ emissions from Ferroalloys Production (CRF category 2.C.2) are included in CRF category 2.C.1.a Steel Production. Production of ferroalloys is a direct production of specialty steels from iron ore via the electric arc furnace process using reductants.
2-D-3	Non-Energy Products from Fuels and Solvent Use – Other (Other and Undifferentiated)	CO ₂ emissions from Carbide Production, Carbon Black Production, Styrene Production, and Ethylene Dichloride and Vinyl Chloride Monomer Production Iron and Steel – Sinter Production Iron and Steel – Pellet Production Metal Industries – Lead Production Metal Industries – Zinc Production Non-Energy Products from Fuels and Solvent Use – Other (Solvent use) Non-Energy Products from Fuels and Solvent Use – natural gas, solid fuels and liquid fuels (including lubricant and paraffin wax use)	Disaggregation of national statistics to broader categories is currently not possible.
2-F	Product Uses as Substitutes for Ozone-Depleting Substances	Refrigeration and Air conditioning Foam Blowing Agents Fire Protection Aerosols Solvents Other Applications	For simplicity reasons, these categories are included in "Product Uses as Substitutes for Ozone Depleting Substances" for the purpose of key category analysis. Efforts will be made to disaggregate these categories in future inventories.
3-A	Agriculture – Enteric Fermentation	Cattle Sheep Swine Other Livestock	For simplicity, the estimates were input by category rather than subcategory. Efforts will be made to disaggregate these categories in future inventories.
3-B	Agriculture – Manure Management	N ₂ O and NMVOC Emissions – Cattle N ₂ O and NMVOC Emissions – Sheep N ₂ O and NMVOC Emissions – Swine N ₂ O and NMVOC Emissions – Other Livestock N ₂ O and NMVOC Emissions – Indirect N ₂ O Emissions	For simplicity, the estimates were input by category rather than subcategory. Efforts will be made to disaggregate these categories in future inventories.
3-D-1	Agriculture – Direct N ₂ O Emissions from Managed Soils	Inorganic N Fertilizers Organic N Fertilizers Urine and Dung Deposited by Grazing Animals Crop Residues Mineralization/Immobilization Associated with Loss/Gain of Soil Organic Matter Cultivation of Organic Soils	For simplicity, the estimates were input by category rather than subcategory. Efforts will be made to disaggregate these categories in future inventories.
3-D-2	Agriculture – Indirect N ₂ O Emissions from Managed Soils	Atmospheric Deposition Nitrogen (N) Leaching and Run-Off	For simplicity, the estimates were input by category rather than subcategory. Efforts will be made to disaggregate these categories in future inventories.
4-A-1	LULUCF – Forest Land Remaining Forest Land	Forest Land Remaining Forest Land Biomass Burning, Forest Land Remaining Forest Land Emissions and removals from drainage, rewetting and other management of organic and mineral soils, Forest Land	To be consistent with the level of land categories at which emission factors, parameters and estimation models are applied. To facilitate the identification, planning and prioritization of efforts needed to improve land category estimates.
4-B-2	LULUCF – Land Converted to Cropland	Land Converted to Cropland Direct N ₂ O emissions from N mineralization/immobilization resulting from change of land use or management of mineral soils Biomass Burning, Land Converted to Cropland	To be consistent with the level of land categories at which emission factors, parameters and estimation models are applied. To facilitate the identification, planning and prioritization of efforts needed to improve land category estimates.
4-C-1	LULUCF – Grassland Remaining Grassland	Grassland Remaining Grassland Biomass Burning, Grassland Remaining Grassland	To be consistent with the level of land categories at which emission factors, parameters and estimation models are applied.
4-D-1	LULUCF – Wetlands Remaining Wetlands	Emissions and removals from drainage, rewetting and other management of organic and mineral soils for peat extraction lands (*only emissions associated with peat extraction remaining peat extraction) Flooded Land Remaining Flooded Land	To be consistent with the level of land categories at which emission factors, parameters and estimation models are applied. To facilitate the identification, planning and prioritization of efforts needed to improve land category estimates.
4-D-2	LULUCF – Land Converted to Wetlands	Land Converted to Flooded Land Emissions and removals from drainage, rewetting and other management of organic and mineral soils, peat extraction lands (*only emissions associated with Land converted to peat extraction) Biomass Burning, Land Converted to Wetlands	To be consistent with the level of land categories at which emission factors, parameters and estimation models are applied. To facilitate the identification, planning and prioritization of efforts needed to improve land category estimates.
4-E-2	LULUCF – Land Converted to Settlements	Land Converted to Settlements Biomass Burning, Settlements	To be consistent with the level of land categories at which emission factors, parameters and estimation models are applied.
5-A-1	Waste – Solid Waste Disposal	Municipal Solid Waste Landfills Wood Waste Landfills	To organize the two landfill sectors together which use similar methodologies

Summary Assessment

Key categories were assessed for the 2020 inventory year using level and trend criteria and for the base year using the level criterion only. There were 35 level key categories in 1990, while in 2020 there were 52 with all combined criteria. Combined assessment results are presented in Table A1–2.

Table A1–2 Key Category Analysis Summary, 2020 Inventory Year

Source Table	IPCC Category	Direct Greenhouse Gas	Key Category (1990 / 2020)		Criteria 1990 / 2020
			Yes	/	L / L , T
1.A.1	Stationary Fuel Combustion – Energy Industries	CO ₂	Yes	/	Yes
1.A.1	Stationary Fuel Combustion – Energy Industries	CH ₄	No	/	Yes
1.A.1	Stationary Fuel Combustion – Energy Industries	N ₂ O	No	/	No
1.A.2	Stationary Fuel Combustion – Manufacturing industries and construction	CO ₂	Yes	/	Yes
1.A.2	Stationary Fuel Combustion – Manufacturing industries and construction	CH ₄	No	/	No
1.A.2	Stationary Fuel Combustion – Manufacturing industries and construction	N ₂ O	No	/	No
1.A.4	Stationary Fuel Combustion – Other sectors	CO ₂	Yes	/	Yes
1.A.4	Stationary Fuel Combustion – Other sectors	CH ₄	No	/	Yes
1.A.4	Stationary Fuel Combustion – Other sectors	N ₂ O	No	/	No
1-A-2-g	Fuel Combustion – Manufacturing Industries and Construction/Other/Off-Road Vehicles and Other Machinery	CO ₂	Yes	/	Yes
1-A-2-g	Fuel Combustion – Manufacturing Industries and Construction/Other/Off-Road Vehicles and Other Machinery	CH ₄	No	/	No
1-A-2-g	Fuel Combustion – Manufacturing Industries and Construction/Other/Off-Road Vehicles and Other Machinery	N ₂ O	No	/	No
1-A-3-a	Fuel Combustion – Domestic Aviation	CO ₂	Yes	/	Yes
1-A-3-a	Fuel Combustion – Domestic Aviation	CH ₄	No	/	No
1-A-3-a	Fuel Combustion – Domestic Aviation	N ₂ O	No	/	No
1-A-3-b	Fuel Combustion – Road Transportation	CO ₂	Yes	/	Yes
1-A-3-b	Fuel Combustion – Road Transportation	CH ₄	No	/	No
1-A-3-b	Fuel Combustion – Road Transportation	N ₂ O	Yes	/	Yes
1-A-3-c	Fuel Combustion – Railways	CO ₂	Yes	/	Yes
1-A-3-c	Fuel Combustion – Railways	CH ₄	No	/	No
1-A-3-c	Fuel Combustion – Railways	N ₂ O	No	/	No
1-A-3-d	Fuel Combustion – Domestic Navigation	CO ₂	No	/	Yes
1-A-3-d	Fuel Combustion – Domestic Navigation	CH ₄	No	/	No
1-A-3-d	Fuel Combustion – Domestic Navigation	N ₂ O	No	/	No
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CO ₂	Yes	/	Yes
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CH ₄	No	/	Yes
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	N ₂ O	No	/	No
1-A-3-e-i	Fuel Combustion – Pipeline Transport	CO ₂	Yes	/	Yes
1-A-3-e-i	Fuel Combustion – Pipeline Transport	CH ₄	No	/	No
1-A-3-e-i	Fuel Combustion – Pipeline Transport	N ₂ O	No	/	No
1-A-4-a	Fuel Combustion – Commercial Institutional/Off-Road Vehicles and Other Machinery	CO ₂	No	/	Yes
1-A-4-a	Fuel Combustion – Commercial Institutional/Off-Road Vehicles and Other Machinery	CH ₄	No	/	No
1-A-4-a	Fuel Combustion – Commercial Institutional/Off-Road Vehicles and Other Machinery	N ₂ O	No	/	No
1-A-4-b	Fuel Combustion – Residential/Off-Road Vehicles and Other Machinery	CO ₂	No	/	Yes
1-A-4-b	Fuel Combustion – Residential/Off-Road Vehicles and Other Machinery	CH ₄	No	/	No
1-A-4-b	Fuel Combustion – Residential/Off-Road Vehicles and Other Machinery	N ₂ O	No	/	No
1-A-4-c	Fuel Combustion – Agriculture Forestry Fishing/Off-Road Vehicles and Other Machinery	CO ₂	Yes	/	Yes
1-A-4-c	Fuel Combustion – Agriculture Forestry Fishing/Off-Road Vehicles and Other Machinery	CH ₄	No	/	No
1-A-4-c	Fuel Combustion – Agriculture Forestry Fishing/Off-Road Vehicles and Other Machinery	N ₂ O	No	/	No
1-B-1-a	Fugitive Emissions – Coal Mining and Handling	CH ₄	Yes	/	Yes
1-A-5-b	Fuel Combustion – Other Mobile (Military Aviation and Navigation)	CO ₂	No	/	No
1-A-5-b	Fuel Combustion – Other Mobile (Military Aviation and Navigation)	CH ₄	No	/	No
1-A-5-b	Fuel Combustion – Other Mobile (Military Aviation and Navigation)	N ₂ O	No	/	No
1-B-2-(a+c)	Fugitive Emissions – Oil	CO ₂	Yes	/	Yes
1-B-2-(a+c)	Fugitive Emissions – Oil	CH ₄	Yes	/	Yes
1-B-2-(a+c)	Fugitive Emissions – Oil	N ₂ O	No	/	No
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CO ₂	Yes	/	Yes
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CH ₄	Yes	/	Yes
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	N ₂ O	No	/	No
1-C-1	CO ₂ Transport and Storage – Pipelines	CO ₂	No	/	No
2-A-1	IPPU – Cement Production	CO ₂	Yes	/	Yes
2-A-2	IPPU – Lime Production	CO ₂	No	/	Yes
2-A-3	IPPU – Glass Production	CO ₂	No	/	No
2-A-4-b	IPPU – Other Uses of Soda Ash	CO ₂	No	/	No
2-A-4-c	IPPU – Other (Magnesite Use)	CO ₂	No	/	No

Table A1–2 Key Category Analysis Summary, 2020 Inventory Year (cont'd)

Source Table	IPCC Category	Direct Greenhouse Gas	Key Category (1990 / 2020)		Criteria 1990 / 2020	
			No	/ Yes	L	T
2-A-4-d	IPPU – Other (Limestone and Dolomite Use Other)	CO ₂				T
2-B-1	IPPU – Ammonia Production	CO ₂	Yes	/ Yes	L	T
2-B-2	IPPU – Nitric Acid Production	N ₂ O	No	/ Yes		T
2-B-3	IPPU – Adipic Acid Production	N ₂ O	Yes	/ Yes	L	T
2-B-7	IPPU – Soda Ash Production	CO ₂	No	/ No		
2-B-8	IPPU – Petrochemical and Carbon Black Production	CO ₂	Yes	/ Yes	L	L
2-B-8	IPPU – Petrochemical and Carbon Black Production (including carbide production)	CH ₄	No	/ No		
2-B-8	IPPU – Petrochemical and Carbon Black Production	N ₂ O	No	/ No		
2-B-9-a	IPPU – Fluorochemical Production	HFCs	No	/ Yes		T
2-C-1	IPPU – Iron and Steel Production	CO ₂	Yes	/ Yes	L	L, T
2-C-1	IPPU – Iron and Steel Production	CH ₄	No	/ No		
2-C-3	IPPU – Aluminium Production	CO ₂	No	/ Yes	L	T
2-C-3	IPPU – Aluminium Production	PFCs	Yes	/ Yes	L	T
2-C-3	IPPU – Aluminium Production	SF ₆	No	/ No		
2-C-4	IPPU – Magnesium Production	SF ₆	No	/ Yes		T
2-C-7	IPPU – Other (Magnesium Casting)	SF ₆	No	/ No		
2-D-3-a	IPPU – Non-Energy Products from Fuels and Solvent Use – Other (Other and Undifferentiated)	CO ₂	Yes	/ Yes	L	L, T
2-D-3-b	IPPU – Non-Energy Products from Fuels and Solvent Use Other – Other (Use of Urea in SCR Vehicles)	CO ₂	No	/ No		
2-E-1	IPPU – Integrated Circuit or Semiconductor	PFCs	No	/ No		
2-E-1	IPPU – Integrated Circuit or Semiconductor	SF ₆	No	/ No		
2-E-1	IPPU – Integrated Circuit or Semiconductor	NF ₃	No	/ No		
2-E-5	IPPU – Other Emissives Applications	PFCs	No	/ No		
2-F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	HFCs	No	/ Yes	L	, T
2-F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	PFCs	No	/ No		
2-G-1	IPPU – Electrical Equipment	SF ₆	No	/ No		
2-G-3-a	IPPU – Other (Medical Applications of N ₂ O)	N ₂ O	No	/ No		
2-G-3-b	IPPU – Other (Use of N ₂ O for Propellant)	N ₂ O	No	/ No		
2-G-4	IPPU – Other Contained Product Uses	PFCs	No	/ No		
3-A	Agriculture – Enteric Fermentation	CH ₄	Yes	/ Yes	L	L, T
3-B	Agriculture – Manure Management	CH ₄	No	/ Yes	L	, T
3-B	Agriculture – Manure Management	N ₂ O	Yes	/ No	L	
3-B-5	Agriculture – Indirect N ₂ O Emissions	N ₂ O	No	/ No		
3-D-1	Agriculture – Direct N ₂ O Emissions from Managed Soils	N ₂ O	Yes	/ Yes	L	L, T
3-D-2	Agriculture – Indirect N ₂ O Emissions from Managed Soils	N ₂ O	No	/ Yes	L	, T
3-F	Agriculture – Field Burning of Agricultural Residues	CH ₄	No	/ No		
3-F	Agriculture – Field Burning of Agricultural Residues	N ₂ O	No	/ No		
3-G-1	Agriculture – Limestone CaCO ₃	CO ₂	No	/ No		
3-H	Agriculture – Urea Application	CO ₂	No	/ Yes		T
3-I	Agriculture – Other Carbon-Containing Fertilizers	CO ₂	No	/ No		
4-A-1	LULUCF – Forest Land Remaining Forest Land	CO ₂	Yes	/ Yes	L	L, T
4-A-1	LULUCF – Forest Land Remaining Forest Land	CH ₄	No	/ No		
4-A-1	LULUCF – Forest Land Remaining Forest Land	N ₂ O	No	/ No		
4-A-2	LULUCF – Land Converted to Forest Land	CO ₂	No	/ No		
4-B-1	LULUCF – Cropland Remaining Cropland	CO ₂	Yes	/ Yes	L	L, T
4-B-2	LULUCF – Land Converted to Cropland	CO ₂	Yes	/ Yes	L	, T
4-B-2	LULUCF – Land Converted to Cropland	CH ₄	No	/ No		
4-B-2	LULUCF – Land Converted to Cropland	N ₂ O	No	/ No		
4-D-1	LULUCF – Wetlands Remaining Wetlands	CO ₂	No	/ Yes		T
4-D-1	LULUCF – Wetlands Remaining Wetlands	CH ₄	No	/ No		
4-D-1	LULUCF – Wetlands Remaining Wetlands	N ₂ O	No	/ No		
4-D-2	LULUCF – Land Converted to Wetlands	CO ₂	Yes	/ Yes	L	, T
4-D-2	LULUCF – Land Converted to Wetlands	CH ₄	No	/ No		
4-D-2	LULUCF – Land Converted to Wetlands	N ₂ O	No	/ No		
4-E-2	LULUCF – Settlements Remaining Settlements	CO ₂	Yes	/ Yes	L	L, T
4-E-2	LULUCF – Land Converted to Settlements	CO ₂	Yes	/ Yes	L	L
4-E-2	LULUCF – Land Converted to Settlements	CH ₄	No	/ No		
4-E-2	LULUCF – Land Converted to Settlements	N ₂ O	No	/ No		
4-C	LULUCF – Grassland	CH ₄	No	/ No		
4-C	LULUCF – Grassland	N ₂ O	No	/ No		
4-G	LULUCF – Harvested Wood Products (HWP)	CO ₂	Yes	/ Yes	L	L, T
5-A-1	Waste – Solid Waste Disposal-Managed Waste Disposal Sites	CH ₄	Yes	/ Yes	L	L
5-A-2	Waste – Solid Waste Disposal-Unmanaged Waste Disposal Sites	CH ₄	Yes	/ Yes	L	T
5-B	Waste – Biological Treatment of Solid Waste	CH ₄	No	/ No		
5-B	Waste – Biological Treatment of Solid Waste	N ₂ O	No	/ No		
5-C-1	Waste – Incineration and Open Burning of Waste	CO ₂	No	/ No		
5-C-1	Waste – Incineration and Open Burning of Waste	N ₂ O	No	/ No		

Table A1-2 Key Category Analysis Summary, 2020 Inventory Year (cont'd)

Source Table	IPCC Category	Direct Greenhouse Gas	Key Category (1990 / 2020)		Criteria 1990 / 2020	
			1990	2020	L: Level	T: Trend
5-C-1	Waste – Incineration and Open Burning of Waste	CH ₄	No	/ No		
5-D-1	Waste – Wastewater Treatment and Discharge	CH ₄	No	/ No		
5-D-1	Waste – Wastewater Treatment and Discharge	N ₂ O	No	/ Yes		T
5-D-1	Waste – Wastewater Treatment and Discharge	CO ₂	No	/ No		

Notes: L = key category by level (for an individual year), T = key category by trend (between the base year and the current year)

A1.2. Key Category Tables

A1.2.1. Level Assessment With and Without LULUCF

Table A1-3 shows the 1990 key categories identified from level assessment with and without LULUCF.

Table A1-4 shows the 2020 key categories identified from level assessment with and without LULUCF.

Table A1-3 1990 Key Categories by Level Assessment With and Without LULUCF

Source Table	IPCC Category	Direct Greenhouse Gas	GHG Emission Estimates (kt CO ₂ eq)		Level Assessment		Cumulative Total	
			Base Year 1990	Current Year 2020	without LULUCF	with LULUCF	without LULUCF	with LULUCF
4-A-1	LULUCF – Forest Land Remaining Forest Land	CO ₂	-201 515	-130 438	NA	0.209	NA	0.209
1.A.1	Stationary Fuel Combustion – Energy Industries	CO ₂	140 866	173 470	0.237	0.146	0.237	0.356
4-G	LULUCF – Harvested Wood Products (HWP)	CO ₂	130 706	127 971	NA	0.136	NA	0.491
1-A-3-b	Fuel Combustion – Road Transportation	CO ₂	80 538	128 784	0.135	0.084	0.372	0.575
1.A.4	Stationary Fuel Combustion – Other Sectors	CO ₂	69 527	75 339	0.117	0.072	0.489	0.647
1.A.2	Stationary Fuel Combustion – Manufacturing Industries and Construction	CO ₂	61 664	45 029	0.104	0.064	0.593	0.711
3-A	Agriculture – Enteric Fermentation	CH ₄	22 347	23 677	0.038	0.023	0.630	0.735
5-A-1	Waste – Solid Waste Disposal-Managed Waste Disposal Sites	CH ₄	19 590	22 135	0.033	0.020	0.663	0.755
1-B-2-(a+c)	Fugitive Emissions – Oil	CH ₄	17 861	17 785	0.030	0.019	0.693	0.773
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CH ₄	16 899	14 681	0.028	0.018	0.722	0.791
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CO ₂	15 451	4 665	0.026	0.016	0.748	0.807
2-C-1	IPPU – Iron and Steel Production	CO ₂	10 478	6 984	0.018	0.011	0.765	0.818
2-B-3	IPPU – Adipic Acid Production	N ₂ O	10 303	0	0.017	0.011	0.783	0.829
1-A-4-c	Fuel Combustion – Agriculture Forestry Fishing/ Off-Road Vehicles and Other Machinery	CO ₂	9 880	11 699	0.017	0.010	0.799	0.839
1-A-2-g	Fuel Combustion – Manufacturing Industries and Construction/Other/Off-Road Vehicles and Other Machinery	CO ₂	9 103	13 843	0.015	0.009	0.815	0.848
4-B-1	LULUCF – Cropland Remaining Cropland	CO ₂	-8 969	-13 072	NA	0.009	NA	0.858
4-B-2	LULUCF – Land Converted to Cropland	CO ₂	8 836	3 288	NA	0.009	NA	0.867
3-D-1	Agriculture – Direct N ₂ O Emissions from Managed Soils	N ₂ O	8 775	16 407	0.015	0.009	0.829	0.876
2-C-3	IPPU – Aluminium Production	PFCs	7 558	770	0.013	0.008	0.842	0.884
1-A-3-a	Fuel Combustion – Domestic Aviation	CO ₂	7 203	4 578	0.012	0.007	0.854	0.891
1-A-3-e-i	Fuel Combustion – Pipeline Transport	CO ₂	6 685	7 494	0.011	0.007	0.865	0.898
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CO ₂	6 202	5 954	0.010	0.006	0.876	0.905
1-A-3-c	Fuel Combustion – Railways	CO ₂	6 200	6 408	0.010	0.006	0.886	0.911
4-E-2	LULUCF – Land Converted to Settlements	CO ₂	5 963	6 417	NA	0.006	NA	0.917
2-A-1	IPPU – Cement Production	CO ₂	5 823	6 625	0.010	0.006	0.896	0.923
2-D-3-a	IPPU – Non-Energy Products from Fuels and Solvent Use – Other (Other and Undifferentiated)	CO ₂	5 804	9 881	0.010	0.006	0.906	0.929
1-B-2-(a+c)	Fugitive Emissions – Oil	CO ₂	5 756	10 103	0.010	0.006	0.916	0.935
4-E-2	LULUCF – Settlements Remaining Settlements	CO ₂	-4 223	-4 422	NA	0.004	NA	0.940
4-D-2	LULUCF – Land Converted to Wetlands	CO ₂	3 926	248	NA	0.004	NA	0.944
2-B-8	IPPU – Petrochemical and Carbon Black Production	CO ₂	3 367	3 776	0.006	0.003	0.921	0.947
1-A-3-b	Fuel Combustion – Road Transportation	N ₂ O	2 923	2 250	0.005	0.003	0.931	NA
1-B-1-a	Fugitive Emissions – Coal Mining and Handling	CH ₄	2 824	1 068	0.005	0.003	0.941	NA
2-B-1	IPPU – Ammonia Production	CO ₂	2 754	2 467	0.005	0.003	0.945	NA
3-B	Agriculture – Manure Management	N ₂ O	3 042	3 290	0.005	0.003	0.926	NA
5-A-2	Waste – Solid Waste Disposal-Unmanaged Waste Disposal Sites	CH ₄	2 869	2 178	0.005	0.003	0.936	NA

Note: NA = Not Applicable

Table A1–4 2020 Key Categories by Level Assessment With and Without LULUCF

Source Table	IPCC Category	Direct Greenhouse Gas	GHG Emission Estimates (kt CO ₂ eq)		Level Assessment		Cumulative Total	
			Base Year 1990	Current Year 2020	without LULUCF	with LULUCF	without LULUCF	with LULUCF
4-A-1	LULUCF – Forest Land Remaining Forest Land	CO ₂	-201 515	-130 438	NA	0.136	NA	0.32
1-A-3-b	Fuel Combustion – Road Transportation	CO ₂	80 538	128 784	0.192	0.134	0.45	0.45
4-G	LULUCF – Harvested Wood Products (HWP)	CO ₂	130 706	127 971	NA	0.133	NA	0.58
1.A.1	Stationary Fuel Combustion – Energy Industries	CO ₂	140 866	173 470	0.258	0.180	0.26	0.18
1.A.2	Stationary Fuel Combustion – Manufacturing industries and Construction	CO ₂	61 664	45 029	0.067	0.047	0.63	0.71
1.A.4	Stationary Fuel Combustion – Other Sectors	CO ₂	69 527	75 339	0.112	0.078	0.56	0.66
3-A	Agriculture – Enteric Fermentation	CH ₄	22 347	23 677	0.035	0.025	0.66	0.73
5-A-1	Waste – Solid Waste Disposal-Managed Waste Disposal Sites	CH ₄	19 590	22 135	0.033	0.023	0.70	0.76
1-B-2-(a+c)	Fugitive Emissions – Oil	CH ₄	17 861	17 785	0.026	0.018	0.72	0.77
3-D-1	Agriculture – Direct N ₂ O Emissions from Managed Soils	N ₂ O	8 775	16 407	0.024	0.017	0.75	0.79
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CH ₄	16 899	14 681	0.022	0.015	0.77	0.81
1-A-2-g	Fuel Combustion – Manufacturing Industries and Construction/Other/Off-Road Vehicles and Other Machinery	CO ₂	9 103	13 843	0.021	0.014	0.79	0.82
4-B-1	LULUCF – Cropland Remaining Cropland	CO ₂	-8 969	-13 072	NA	0.014	NA	0.83
2-F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	HFCs	0	11 944	0.018	0.012	0.81	0.85
1-A-4-c	Fuel Combustion – Agriculture Forestry Fishing/Off-Road Vehicles and Other Machinery	CO ₂	9 880	11 699	0.017	0.012	0.83	0.86
1-B-2-(a+c)	Fugitive Emissions – Oil	CO ₂	5 756	10 103	0.015	0.011	0.84	0.87
2-D-3-a	IPPU – Non-Energy Products from Fuels and Solvent Use – Other (Other and Undifferentiated)	CO ₂	5 804	9 881	0.015	0.010	0.85	0.88
1-A-3-e-i	Fuel Combustion – Pipeline Transport	CO ₂	6 685	7 494	0.011	0.008	0.87	0.89
2-C-1	IPPU – Iron and Steel Production	CO ₂	10 478	6 984	0.010	0.007	0.88	0.89
2-A-1	IPPU – Cement Production	CO ₂	5 823	6 625	0.010	0.007	0.89	0.90
4-E-2	LULUCF – Land Converted to Settlements	CO ₂	5 963	6 417	NA	0.007	NA	0.91
1-A-3-c	Fuel Combustion – Railways	CO ₂	6 200	6 408	0.010	0.007	0.90	0.91
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CO ₂	6 202	5 954	0.009	0.006	0.90	0.92
2-C-3	IPPU – Aluminium Production	CO ₂	2 715	5 131	0.008	0.005	0.91	0.93
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CO ₂	15 451	4 665	0.007	0.005	0.92	0.93
1-A-3-a	Fuel Combustion – Domestic Aviation	CO ₂	7 203	4 578	0.007	0.005	0.93	0.94
4-E-2	LULUCF – Settlements Remaining Settlements	CO ₂	-4 223	-4 422	NA	0.005	NA	0.94
3-D-2	Agriculture – Indirect N ₂ O Emissions from Managed Soils	N ₂ O	2 560	4 194	0.006	0.004	0.93	0.95
3-B	Agriculture – Manure Management	CH ₄	2 461	3 891	0.006	0.004	0.94	0.95
1-A-3-d	Fuel Combustion – Domestic Navigation	CO ₂	2 149	3 810	0.006	0.004	0.94	NA
2-B-8	IPPU – Petrochemical and Carbon Black Production	CO ₂	3 367	3 776	0.006	0.004	0.95	NA

Note: NA = Not Applicable

A1.2.2. Trend Assessment With and Without LULUCF

Table A1–5 and Table A1–6 show the key categories indicated from the trend assessment without and with LULUCF, respectively. These tables also show the contribution of the key categories to the trend assessment.

The integration of the LULUCF sector introduces additional key categories and alters the categories' relative contributions and overall trends, which causes a rearrangement in the ranking of key categories. For example, a single LULUCF category, Forest Land Remaining Forest Land (CO₂), is ranked as the second highest contributor in the trend assessments.

The trend assessment without LULUCF identifies 41 key categories, while the same analysis with LULUCF results in 42 key categories, including seven categories from the LULUCF sector.

Table A1–5 Key Categories by Trend Assessment without LULUCF

Source Table	IPCC Category	Direct Greenhouse Gas	GHG Emission Estimates (kt CO ₂ eq)		Trend Assessment	Contribution to Trend	Cumulative Total
			Base Year 1990	Current Year 2020			
1-A-3-b	Fuel Combustion – Road Transportation	CO ₂	80 538	128 784	0.063	0.192	0.19
1.A.2	Stationary Fuel Combustion – Manufacturing industries and construction	CO ₂	61 664	45 029	0.042	0.126	0.32
1.A.1	Stationary Fuel Combustion – Energy Industries	CO ₂	140 866	173 470	0.024	0.072	0.39
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CO ₂	15 451	4 665	0.022	0.065	0.46
2-F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	HFCs	0	11 944	0.020	0.061	0.52
2-B-3	IPPU – Adipic Acid Production	N ₂ O	10 303	0	0.020	0.059	0.58
2-C-3	IPPU – Aluminium Production	PFCs	7 558	770	0.013	0.040	0.62
3-D-1	Agriculture – Direct N ₂ O Emissions from Managed Soils	N ₂ O	8 775	16 407	0.011	0.033	0.65
2-C-1	IPPU – Iron and Steel Production	CO ₂	10 478	6 984	0.008	0.025	0.67
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CH ₄	16 899	14 681	0.007	0.023	0.70
1-B-2-(a+c)	Fugitive Emissions – Oil	CO ₂	5 756	10 103	0.006	0.018	0.72
1-A-3-a	Fuel Combustion – Domestic Aviation	CO ₂	7 203	4 578	0.006	0.018	0.73
1-A-2-g	Fuel Combustion – Manufacturing Industries and Construction/Other/Off-Road Vehicles and Other Machinery	CO ₂	9 103	13 843	0.006	0.018	0.75
2-D-3-a	IPPU – Non-Energy Products from Fuels and Solvent Use – Other (Other and Undifferentiated)	CO ₂	5 804	9 881	0.006	0.017	0.77
1.A.4	Stationary Fuel Combustion – Other Sectors	CO ₂	69 527	75 339	0.005	0.017	0.79
2-C-4	IPPU – Magnesium Production	SF ₆	2 738	0	0.005	0.016	0.80
1-B-2-(a+c)	Fugitive Emissions – Oil	CH ₄	17 861	17 785	0.004	0.012	0.81
1-B-1-a	Fugitive Emissions – Coal Mining and Handling	CH ₄	2 824	1 068	0.004	0.011	0.82
2-C-3	IPPU – Aluminium Production	CO ₂	2 715	5 131	0.003	0.011	0.83
1-A-4-b	Fuel Combustion – Residential/Off-Road Vehicles and Other Machinery	CO ₂	9 880	11 699	0.003	0.009	0.84
3-H	Agriculture – Urea Application	CO ₂	754	2 521	0.003	0.009	0.85
3-A	Agriculture – Enteric Fermentation	CH ₄	22 347	23 677	0.003	0.008	0.86
1-A-3-d	Fuel Combustion – Domestic Navigation	CO ₂	2 149	3 810	0.002	0.007	0.87
3-D-2	Agriculture – Indirect N ₂ O Emissions from Managed Soils	N ₂ O	2 560	4 194	0.002	0.007	0.87
1-A-4-c	Fuel Combustion – Agriculture Forestry Fishing/Off-Road Vehicles and Other Machinery	CO ₂	2 824	1 068	0.002	0.006	0.88
1.A.4	Stationary Fuel Combustion – Other Sectors	CH ₄	2 206	1 357	0.002	0.006	0.89
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CH ₄	1 235	280	0.002	0.006	0.89
3-B	Agriculture – Manure Management	CH ₄	2 461	3 891	0.002	0.006	0.90
2-B-9-a	IPPU – Fluorochemical Production	HFCs	971	0	0.002	0.006	0.90
5-A-2	Waste – Solid Waste Disposal-Unmanaged Waste Disposal Sites	CH ₄	2 869	2 178	0.002	0.005	0.91
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CO ₂	6 202	5 954	0.002	0.005	0.91
1-A-3-b	Fuel Combustion – Road Transportation	N ₂ O	2 923	2 250	0.002	0.005	0.92
2-B-2	IPPU – Nitric Acid Production	N ₂ O	973	189	0.002	0.005	0.92
2-A-2	IPPU – Lime Production	CO ₂	1 806	1 193	0.001	0.004	0.93
1.A.1	Stationary Fuel Combustion – Energy Industries	CH ₄	1 520	2 506	0.001	0.004	0.93
1-A-4-a	Fuel Combustion – Commercial Institutional/Off-Road Vehicles and Other Machinery	CO ₂	236	1 157	0.001	0.004	0.94
2-B-1	IPPU – Ammonia Production	CO ₂	2 754	2 467	0.001	0.003	0.94
1-A-3-c	Fuel Combustion – Railways	CO ₂	6 200	6 408	0.001	0.003	0.94
5-D-1	Waste – Wastewater Treatment and Discharge	N ₂ O	798	1 419	0.001	0.003	0.95
2-A-4-d	IPPU – Other (Limestone and Dolomite Use Other)	CO ₂	449	98	0.001	0.002	0.95
1-A-3-e-i	Fuel Combustion – Pipeline Transport	CO ₂	1 492	2 754	0.001	0.002	0.95

Table A1–6 Key Categories by Trend Assessment with LULUCF

Source Table	IPCC Category	Direct Greenhouse Gas	GHG Emission Estimates (kt CO ₂ eq)		Trend Assessment	Contribution to Trend	Cumulative Total
			Base Year 1990	Current Year 2020			
4-A-1	LULUCF – Forest Land Remaining Forest Land	CO ₂	-201 515	-130 438	0.045	0.153	0.15
1-A-3-b	Fuel Combustion – Road Transportation	CO ₂	80 538	128 784	0.038	0.132	0.29
1.A.2	Stationary Fuel Combustion – Manufacturing Industries and Construction	CO ₂	61 664	45 029	0.026	0.090	0.38
4-G	LULUCF – Harvested Wood Products (HWP)	CO ₂	130 706	127 971	0.022	0.075	0.45
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CO ₂	15 451	4 665	0.013	0.046	0.50
1.A.1	Stationary Fuel Combustion – Energy Industries	CO ₂	140 866	173 470	0.013	0.046	0.54
2-F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	HFCs	0	11 944	0.012	0.043	0.59
2-B-3	IPPU – Adipic Acid Production	N ₂ O	10 303	0	0.012	0.042	0.63
2-C-3	IPPU – Aluminium Production	PFCs	7 558	770	0.008	0.028	0.66
4-B-2	LULUCF – Land Converted to Cropland	CO ₂	8 836	3 288	0.007	0.024	0.68
3-D-1	Agriculture – Direct N ₂ O Emissions from Managed Soils	N ₂ O	8 775	16 407	0.007	0.023	0.70
4-B-1	LULUCF – Cropland Remaining Cropland	CO ₂	-8 969	-13 072	0.006	0.019	0.72
2-C-1	IPPU – Iron and Steel Production	CO ₂	10 478	6 984	0.005	0.018	0.74
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CH ₄	16 899	14 681	0.005	0.016	0.76
4-D-2	LULUCF – Land Converted to Wetlands	CO ₂	3 926	248	0.004	0.015	0.77
1.A.4	Stationary Fuel Combustion – Other sectors	CO ₂	69 527	75 339	0.004	0.014	0.78
1-A-3-a	Fuel Combustion – Domestic Aviation	CO ₂	7 203	4 578	0.004	0.013	0.80
1-B-2-(a+c)	Fugitive Emissions – Oil	CO ₂	5 756	10 103	0.004	0.013	0.81
1-A-2-g	Fuel Combustion – Manufacturing Industries and Construction/Other/Off-Road Vehicles and Other Machinery	CO ₂	9 103	13 843	0.004	0.012	0.82
2-D-3-a	IPPU – Non-Energy Products from Fuels and Solvent Use – Other (Other and Undifferentiated)	CO ₂	5 804	9 881	0.003	0.012	0.83
2-C-4	IPPU – Magnesium Production	SF ₆	2 738	0	0.003	0.011	0.85
1-B-2-(a+c)	Fugitive Emissions – Oil	CH ₄	17 861	17 785	0.003	0.009	0.85
1-B-1-a	Fugitive Emissions – Coal Mining and Handling	CH ₄	2 824	1 068	0.002	0.008	0.86
2-C-3	IPPU – Aluminium Production	CO ₂	2 715	5 131	0.002	0.007	0.87
3-A	Agriculture – Enteric Fermentation	CH ₄	22 347	23 677	0.002	0.006	0.88
1-A-4-b	Fuel Combustion – Residential/Off-Road Vehicles and Other Machinery	CO ₂	9 880	11 699	0.002	0.006	0.88
3-H	Agriculture – Urea Application	CO ₂	754	2 521	0.002	0.006	0.89
1-A-4-c	Fuel Combustion – Agriculture Forestry Fishing/Off-Road Vehicles and Other Machinery	CO ₂	2 824	1 068	0.001	0.005	0.90
3-D-2	Agriculture – Indirect N ₂ O Emissions from Managed Soils	N ₂ O	2 560	4 194	0.001	0.005	0.90
1.A.4	Stationary Fuel Combustion – Other Sectors	CH ₄	2 206	1 357	0.001	0.004	0.91
1-A-3-e-ii	Fuel Combustion – Other Transport (Off Road)	CH ₄	1 235	280	0.001	0.004	0.91
1-B-2-(b+c)	Fugitive Emissions – Natural Gas	CO ₂	6 202	5 954	0.001	0.004	0.91
2-B-9-a	IPPU – Fluorochemical Production	HFCs	971	0	0.001	0.004	0.92
5-A-2	Waste – Solid Waste Disposal-Unmanaged Waste Disposal Sites	CH ₄	2 869	2 178	0.001	0.004	0.92
3-B	Agriculture – Manure Management	CH ₄	2 461	3 891	0.001	0.004	0.93
1-A-3-b	Fuel Combustion – Road Transportation	N ₂ O	2 923	2 250	0.001	0.004	0.93
4-D-1	LULUCF – Wetlands remaining Wetlands	CO ₂	1 456	2 643	0.001	0.004	0.93
2-B-2	IPPU – Nitric Acid Production	N ₂ O	973	189	0.001	0.003	0.94
2-A-2	IPPU – Lime Production	CO ₂	1 806	1 193	0.001	0.003	0.94
4-E-2	LULUCF – Settlements Remaining Settlements	CO ₂	-4 223	-4 422	0.001	0.003	0.94
1.A.1	Stationary Fuel Combustion – Energy Industries	CH ₄	1 520	2 506	0.001	0.003	0.95
1-A-4-a	Fuel Combustion – Commercial Institutional/Off-Road Vehicles and Other Machinery	CO ₂	236	1 157	0.001	0.003	0.95

ANNEX 2

UNCERTAINTY

Table A2–1	Uncertainty Assessment Level for base year and latest year without Land Use, Land-Use Change and Forestry	12
Table A2–2	Uncertainty Assessment Level for base year and latest year with Land Use, Land-Use Change and Forestry	15

A2.1. Introduction

All Annex I Parties to the United Nations Framework Convention on Climate Change are required to report estimated uncertainties associated with both annual estimates of emissions and emission trends over time in their respective national inventory reports. Uncertainty analysis helps to prioritize improvements of future inventories and to guide decisions on methodological choice (IPCC, 2006).

In this submission, Canada used the error propagation method (Approach 1) for combining uncertainties, as outlined in Volume 1 (Chapter 3) of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006), to assess the uncertainty in emission estimates for the base year and the latest year. Uncertainty estimates were combined by completing Table 3.3 at the source category level. Uncertainty estimates for each source/sink category were either retained from previous studies (e.g. a comprehensive Monte Carlo analysis (Approach 2) conducted in 2003/2004), improved upon on the basis of these studies, or derived independently as in the Agriculture (methane [CH_4] and nitrous oxide [N_2O]), Energy (some fuel combustion categories and fugitive emissions), Industrial Processes and Product Use (IPPU) and Land Use, Land-Use Change and Forestry (LULUCF) sectors. For details on uncertainty related to specific sectors, refer to the uncertainty sections throughout Chapters 3 to 7.

A2.2. Interpretation of Uncertainty about Inventory Estimates

Often uncertainty about GHG estimates is incorrectly interpreted as a measure of accuracy or reliability. In fact, accuracy (or its inverse, bias) can only be quantified by measuring departure from the truth. Uncertainty estimation for inventories is not designed as a measure of accuracy, rather in the context of national inventories, the process of uncertainty estimation mostly aims to quantify precision. High uncertainty about a category estimate suggests it would be difficult to obtain agreement among repeated measurements. This can arise from many factors, including true heterogeneity over time and space: variability is an inherent property of many systems, including nature.

In IPCC good practice guidance, uncertainty information is primarily a “means to help prioritise efforts to improve the accuracy of inventories in the future and guide decisions on methodological choice, ...” (IPCC, 2006, vol 1, chapter 3). Minimizing bias and obtaining reliable estimates are better achieved by implementing good practice in estimate development.

A2.3. Uncertainty Assessment on 2020 Greenhouse Gas Emissions and Removals

Separate analyses were conducted for the inventory as a whole with and without LULUCF. The 2020 national emission estimate (not including the LULUCF sector) of 672 Mt CO_2 eq lies within an uncertainty range of 652 Mt CO_2 eq to 693 Mt CO_2 eq ($\pm 3\%$) (Table A2–1). The Energy sector has the lowest uncertainty, at $\pm 1\%$, while the Waste sector has the highest uncertainty, at $\pm 63\%$. The IPPU sector and the Agriculture sector have uncertainties of ± 5 , and $\pm 15\%$, respectively. The five emission source categories that made the largest contributions to uncertainty at the national level, for 2020, when LULUCF is not included were:

1. Waste – Solid Waste Disposal – Managed Waste Disposal Sites, CH_4
2. Agriculture – Direct Agriculture Soils, N_2O
3. Agriculture – Enteric Fermentation, CH_4
4. Agriculture – Indirect Agriculture Soils, N_2O
5. Waste – Solid Waste Disposal – Unmanaged Waste Disposal Sites – Wood Waste Landfills, CH_4

The 2020 national emission estimate, including LULUCF emissions and removals, of 666 Mt CO₂ eq, lies within an uncertainty range of 612 Mt CO₂ eq to 719 Mt CO₂ eq ($\pm 8\%$) (Table A2–2). The top five contributors influencing the national uncertainty when LULUCF is included were:

1. Waste – Solid Waste Disposal – Managed Waste Disposal Sites, CH₄
2. LULUCF – Harvested Wood Products (HWP), CO₂
3. Agriculture – Direct Agriculture Soils, N₂O
4. Agriculture – Enteric Fermentation, CH₄
5. Agriculture – Indirect Agriculture Soils, N₂O

A2.4. Uncertainty Assessment on base year Greenhouse Gas Emissions and Removals

The uncertainty for the base year of the national emission estimate (not including the LULUCF sector) is similar to 2020 uncertainty ($\pm 3\%$) (Table A2–1). The five emission source categories that made the largest contributions to uncertainty at the national level, for 1990, when LULUCF is not included are:

1. Waste – Solid Waste Disposal – Managed Waste Disposal Sites, CH₄
2. Waste – Solid Waste Disposal – Unmanaged Waste Disposal Sites – Wood Waste Landfills, CH₄
3. Energy – Fuel Combustion – Public Electricity and Heat Production, CO₂
4. Agriculture – Enteric Fermentation, CH₄
5. Agriculture – Direct Agriculture Soils, N₂O

When LULUCF emissions and removals is included, the uncertainty for the base year is different from 2020 uncertainty ($\pm 14\%$) (Table A2–2). The top five contributors influencing the national uncertainty for 1990 when LULUCF is included are:

1. LULUCF – Harvested Wood Products (HWP), CO₂
2. Waste – Solid Waste Disposal – Managed Waste Disposal Sites, CH₄
3. Waste – Solid Waste Disposal – Unmanaged Waste Disposal Sites – Wood Waste Landfills, CH₄
4. Energy – Fuel Combustion – Public Electricity and Heat Production, CO₂
5. Agriculture – Enteric Fermentation, CH₄

A2.5. Planned Improvements

Continuous improvement is one of the principles upon which Canada develops its annual GHG inventory. Planned improvements associated with uncertainty assessment will likely build on previous methods and databases, including making use of the Monte Carlo simulation data and methods performed in 2003–2004. New methodological changes and refinements consider the impact on uncertainty prior to implementation and therefore provide a basis for regular incremental improvement to the uncertainty analysis.

Uncertainty estimation of national emissions is the topic of a working paper to be released in 2020 (Laferrière et al., 2020). This study compares actual Tier 1 uncertainty estimates with a more general approach, namely Monte Carlo simulations. The comparison highlights:

- the impact on emissions uncertainty related with asymmetrical probability distribution function (PDF) and PDF other than normal;
- the effect of incorporating emission correlation across IPCC source category—often, it is difficult to justify the Tier 1 assumption that emission factors are uncorrelated across categories—the paper shows the importance of its recognition and compares trend uncertainty and category contribution to uncertainty; and
- the possibility to factor in dual uncertainty levels for the activity variables (for example, categories comprised of multiple activity datasets may individually have high uncertainty values but when aggregated the final result may have a lower uncertainty value).

Results of the recent uncertainty analysis were used for the category of Product Uses as Substitutes for Ozone Depleting Substance – HFCs. Improvements with respect to uncertainty estimates will continue for other categories in future inventories. Chapter 8 provides a summary of planned improvements.

Table A2-1 Uncertainty Assessment Level for base year and latest year without Land Use, Land-Use Change and Forestry

IPCC Source Category	Gas	Emissions		Activity Data Uncertainty ^a		Emission Factor Uncertainty ^a		Combined Uncertainty		Combined Uncertainty as % of TOTAL		
		Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	
		kt CO ₂ eq	kt CO ₂ eq	%	%	%	%	%	%	%	%	
TOTALS		594 722	672 416	2.10	2.00	1.70	1.80	3.10	3.00			
1.A.1.a	Fuel Combustion – Public Electricity and Heat Production	CO ₂	93 982	61 580	5.30	0.47	0.49	4.20	5.30	4.20	0.83	0.38
1.A.1.a	Fuel Combustion – Public Electricity and Heat Production	CH ₄	44	160	0.68	0.68	28.00	28.00	28.00	28.00	0.00	0.01
1.A.1.a	Fuel Combustion – Public Electricity and Heat Production	N ₂ O	492	391	0.48	0.48	180.00	180.00	180.00	180.00	0.15	0.10
1.A.1.b	Fuel Combustion – Petroleum Refining	CO ₂	17 300	14 386	0.93	0.92	8.80	8.80	8.80	8.90	0.26	0.19
1.A.1.b	Fuel Combustion – Petroleum Refining	CH ₄	11	8	0.81	0.81	200.00	200.00	200.00	200.00	0.00	0.00
1.A.1.b	Fuel Combustion – Petroleum Refining	N ₂ O	50	32	0.68	0.68	310.00	310.00	310.00	310.00	0.03	0.02
1.A.1.c	Fuel Combustion – Manufacture of Solid Fuels and Other Energy Industries	CO ₂	29 583	97 504	3.00	0.86	0.84	2.40	3.10	2.50	0.16	0.37
1.A.1.c	Fuel Combustion – Manufacture of Solid Fuels and Other Energy Industries	CH ₄	1 465	2 338	1.00	1.00	120.00	120.00	120.00	120.00	0.29	0.42
1.A.1.c	Fuel Combustion – Manufacture of Solid Fuels and Other Energy Industries	N ₂ O	197	574	0.93	0.93	440.00	440.00	440.00	440.00	0.14	0.37
1.A.2	Fuel Combustion – Manufacturing Industries and Construction	CO ₂	61 664	45 029	2.30	2.60	3.60	3.50	3.80	3.90	0.39	0.26
1.A.2	Fuel Combustion – Manufacturing Industries and Construction	CH ₄	64	62	2.60	2.60	26.00	26.00	26.00	26.00	0.00	0.00
1.A.2	Fuel Combustion – Manufacturing Industries and Construction	N ₂ O	483	480	2.70	2.70	41.00	41.00	41.00	41.00	0.03	0.03
1.A.2-3-42	Fuel Combustion -Off-Road ^b	CO ₂	35 295	33 887	1.20	1.10	0.13	0.11	1.20	1.10	0.07	0.06
1.A.2-3-42	Fuel Combustion -Off-Road ^b	CH ₄	1 288	499	1.60	1.10	32.00	11.00	32.00	11.00	0.07	0.01
1.A.2-3-42	Fuel Combustion -Off-Road ^b	N ₂ O	118	467	0.97	1.80	280.00	68.00	280.00	68.00	0.06	0.05
1.A.3.a	Fuel Combustion – Civil Aviation	CO ₂	7 203	4 578	0.79	0.77	0.47	0.41	0.92	0.87	0.01	0.01
1.A.3.a	Fuel Combustion – Civil Aviation	CH ₄	11	4	0.80	0.77	220.00	220.00	220.00	220.00	0.00	0.00
1.A.3.a	Fuel Combustion – Civil Aviation	N ₂ O	67	40	0.72	0.72	650.00	650.00	650.00	650.00	0.07	0.04
1.A.3.b	Fuel Combustion – Road Transportation	CO ₂	80 538	128 784	0.80	1.20	0.10	0.13	0.81	1.20	0.11	0.23
1.A.3.b	Fuel Combustion – Road Transportation	CH ₄	308	207	0.78	1.10	14.00	110.00	14.00	110.00	0.01	0.03
1.A.3.b	Fuel Combustion – Road Transportation	N ₂ O	2 923	2 250	1.20	1.30	33.00	41.00	33.00	41.00	0.16	0.14
1.A.3.c	Fuel Combustion – Railways	CO ₂	6 200	6 408	3.00	3.00	0.28	0.28	3.00	3.00	0.03	0.03
1.A.3.c	Fuel Combustion – Railways	CH ₄	9	9	3.00	3.10	150.00	150.00	150.00	150.00	0.00	0.00
1.A.3.c	Fuel Combustion – Railways	N ₂ O	709	750	3.00	3.10	200.00	200.00	200.00	200.00	0.24	0.22
1.A.3.d	Fuel Combustion – Navigation	CO ₂	2 149	3 810	2.10	2.70	1.70	0.39	2.80	2.70	0.01	0.02
1.A.3.d	Fuel Combustion – Navigation	CH ₄	5	9	2.10	2.80	36.00	45.00	36.00	45.00	0.00	0.00
1.A.3.d	Fuel Combustion – Navigation	N ₂ O	17	31	2.10	2.80	100.00	130.00	100.00	130.00	0.00	0.01
1.A.3.e	Fuel Combustion – Pipeline Transport	CO ₂	6 685	7 494	0.99	0.99	0.71	0.90	1.20	1.30	0.01	0.01
1.A.3.e	Fuel Combustion – Pipeline Transport	CH ₄	167	182	1.00	1.00	15.00	15.00	15.00	15.00	0.00	0.00
1.A.3.e	Fuel Combustion – Pipeline Transport	N ₂ O	53	57	1.00	1.00	490.00	490.00	490.00	490.00	0.04	0.04
1.A.4	Fuel Combustion – Other Sectors	CO ₂	69 527	75 339	1.40	2.00	1.90	1.50	2.00	2.20	0.24	0.25
1.A.4	Fuel Combustion – Other Sectors	CH ₄	2 206	1 357	5.70	5.70	16.00	16.00	16.00	16.00	0.06	0.03
1.A.4	Fuel Combustion – Other Sectors	N ₂ O	638	656	4.20	4.20	30.00	30.00	30.00	30.00	0.03	0.03
1.A.4.c.iii	Fuel Combustion – Fishing	CO ₂	866	230	11.00	3.70	1.00	0.35	11.00	3.70	0.02	0.00
1.A.4.c.iii	Fuel Combustion – Fishing	CH ₄	2	1	18.00	22.00	300.00	370.00	300.00	370.00	0.00	0.00
1.A.4.c.iii	Fuel Combustion – Fishing	N ₂ O	7	2	11.00	3.60	500.00	170.00	500.00	170.00	0.01	0.00
1.A.5.b.	Fuel Combustion – Other (Military Aviation)	CO ₂	231	185	0.62	0.64	0.31	0.32	0.69	0.72	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Aviation)	CH ₄	0	0	0.83	0.51	740.00	440.00	740.00	440.00	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Aviation)	N ₂ O	2	2	0.61	0.64	550.00	580.00	550.00	580.00	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Navigation)	CO ₂	28	107	0.36	1.70	0.03	0.16	0.36	1.70	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Navigation)	CH ₄	0	0	0.58	11.00	9.80	170.00	9.80	170.00	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Navigation)	N ₂ O	0	1	0.35	1.80	16.00	78.00	16.00	78.00	0.00	0.00

Table A2–1 Uncertainty Assessment Level for base year and latest year without Land Use, Land-Use Change and Forestry (cont'd)

IPCC Source Category	Gas	Emissions		Activity Data Uncertainty ^a		Emission Factor Uncertainty ^a		Combined Uncertainty		Combined Uncertainty as % of TOTAL		
		Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	
		kt CO ₂ eq	kt CO ₂ eq	%	%	%	%	%	%	%	%	
1.B.1.a	Fugitive Sources – Coal Mining	CH ₄	2 824	1 068	0.00	0.00	0.00	0.00	57.00	57.00	0.27	0.09
1.B.2.(a+b)	Fugitive Sources – Oil & Gas	CO ₂	99	631	0.00	0.00	0.00	0.00	31.00	29.00	0.01	0.03
1.B.2.(a+b)	Fugitive Sources – Oil & Gas	CH ₄	18 787	19 740	0.00	0.00	0.00	0.00	6.00	8.00	0.19	0.23
1.B.2.(a+b)	Fugitive Sources – Oil & Gas	N ₂ O	30	91	0.00	0.00	0.00	0.00	300.00	300.00	0.02	0.04
1.B.2.c	Fugitive Sources – Venting	CO ₂	7 000	9 609	0.00	0.00	0.00	0.00	18.00	26.00	0.21	0.37
1.B.2.c	Fugitive Sources – Flaring	CO ₂	4 859	5 817	0.00	0.00	0.00	0.00	10.00	8.00	0.08	0.07
1.B.2.c	Fugitive Sources – Venting & Flaring	CH ₄	15 973	12 725	0.00	0.00	0.00	0.00	7.00	5.00	0.19	0.09
1.B.2.c	Fugitive Sources – Venting & Flaring	N ₂ O	2	7	0.00	0.00	0.00	0.00	54.00	120.00	0.00	0.00
1.C	CO ₂ Transport and Storage	CO ₂	-	0	0.00	2.00	0.00	100.00	0.00	100.00	0.00	0.00
2.A.1	IPPU – Cement Production	CO ₂	5 823	6 625	0.00	0.00	0.00	0.00	14.00	8.50	0.00	0.00
2.A.2	IPPU – Lime Production	CO ₂	1 806	1 193	36.00	8.00	2.00	2.00	31.00	6.70	0.00	0.00
2.A.3	IPPU – Glass Production	CO ₂	166	43	0.00	0.00	0.00	0.00	14.00	10.00	0.00	0.00
2.A.4.b	IPPU – Other Uses of Soda Ash	CO ₂	100	46	0.00	0.00	0.00	0.00	7.50	6.00	0.00	0.00
2.A.4.c	IPPU – Other (Magnesite Use)	CO ₂	147	116	5.50	7.80	2.00	2.10	5.80	8.10	0.00	0.00
2.A.4.d	IPPU – Other (Limestone and Dolomite Use)	CO ₂	449	98	0.00	0.00	0.00	0.00	32.00	32.00	0.00	0.00
2.B.1	IPPU – Ammonia Production	CO ₂	2 754	2 467	2.20	1.40	9.00	10.00	6.70	6.90	0.00	0.00
2.B.2	IPPU – Nitric Acid Production	N ₂ O	973	189	2.00	2.00	10.00	10.00	2.20	1.10	0.00	0.00
2.B.3	IPPU – Adipic Acid Production	N ₂ O	10 303	-	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00
2.B.7	IPPU – Soda Ash Production	CO ₂	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.B.8	IPPU – Petrochemical and Carbon Black Production	CO ₂	3 367	3 776	0.00	0.00	0.00	0.00	4.20	3.10	0.00	0.00
2.B.8	IPPU – Petrochemical and Carbon Black Production (including carbide production)	CH ₄	134	141	0.00	0.00	0.00	0.00	13.00	17.00	0.00	0.00
2.B.8	IPPU – Petrochemical and Carbon Black Production	N ₂ O	15	13	0.00	0.00	0.00	0.00	8.10	10.00	0.00	0.00
2.B.9.a	IPPU – Fluorochemical Production	HFCs	971	-	0.00	0.00	0.00	0.00	50.00	0.00	0.08	0.00
2.C.1	IPPU – Iron and Steel Production	CO ₂	10 478	6 984	0.00	0.00	0.00	0.00	5.50	5.60	0.00	0.00
2.C.1	IPPU – Iron and Steel Production	CH ₄	2	2	0.00	0.00	0.00	0.00	410.00	410.00	0.00	0.00
2.C.3	IPPU – Aluminium Production	CO ₂	2 715	5 131	0.00	0.00	0.00	0.00	15.00	7.10	0.00	0.00
2.C.3	IPPU – Aluminium Production	PFCs	7 558	770	0.00	0.00	0.00	0.00	18.00	9.10	0.00	0.00
2.C.3	IPPU – Aluminium Production	SF ₆	56	1	0.00	0.00	0.00	0.00	1.00	3.30	0.00	0.00
2.C.4	IPPU – Magnesium Production	SF ₆	2 738	-	0.00	0.00	0.00	0.00	4.20	0.00	0.00	0.00
2.C.7	IPPU – Other (Magnesium Casting)	SF ₆	225	102	0.00	0.00	0.00	0.00	4.40	6.40	0.00	0.00
2.D.3.a	IPPU – Non-Energy Products from Fuels and Solvent Use Other – Other (Other and Undifferentiated)	CO ₂	5 804	9 881	0.00	0.00	0.00	0.00	29.00	20.00	0.00	0.00
2.D.3.b	IPPU – Non-Energy Products from Fuels and Solvent Use Other – Other (Use of Urea in SCR Vehicles)	CO ₂	-	28	0.00	0.00	0.00	0.00	50.00	50.00	0.00	0.00
2.E.1	IPPU – Integrated Circuit or Semiconductor	PFCs	0	11	250.00	2.00	200.00	19.00	320.00	19.00	0.00	0.00
2.E.1	IPPU – Integrated Circuit or Semiconductor	SF ₆	4	35	15.00	15.00	30.00	30.00	45.00	45.00	0.00	0.00
2.E.1	IPPU – Integrated Circuit or Semiconductor	NF ₃	0	1	250.00	2.00	70.00	300.00	260.00	300.00	0.00	0.00
2.E.5	IPPU – Other Emissive Applications	PFCs	-	0	0.00	2.00	0.00	50.00	0.00	50.00	0.00	0.00
2.F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	HFCs	-	11 944	0.00	0.00	0.00	0.00	0.00	11.00	0.00	0.00
2.F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	PFCs	-	9	0.00	0.00	0.00	0.00	0.00	23.00	0.00	0.00
2.G.1	IPPU – Electrical Equipment	SF ₆	202	165	11.00	11.00	30.00	30.00	32.00	32.00	0.00	0.00
2.G.3.a	IPPU – Other (Medical Applications of N ₂ O)	N ₂ O	146	454	20.00	20.00	5.00	5.00	18.00	20.00	0.00	0.00
2.G.3.b	IPPU – Other (Uses of N ₂ O for Propellant)	N ₂ O	26	83	20.00	20.00	5.00	5.00	18.00	20.00	0.00	0.00
2.G.4	IPPU – Other Contained Product Uses	PFCs	-	24	0.00	2.00	0.00	50.00	0.00	51.00	0.00	0.00
	Agriculture – Total CH ₄	CH ₄	24 978	27 608	0.00	0.00	0.00	0.00	20.00	19.00	0.84	0.80
3.A	Agriculture – Enteric Fermentation	CH ₄	22 347	23 677	0.00	0.00	0.00	0.00	22.00	22.00	0.83	0.77

Table A2–1 Uncertainty Assessment Level for base year and latest year without Land Use, Land-Use Change and Forestry (cont'd)

IPCC Source Category	Gas	Emissions		Activity Data Uncertainty ^a		Emission Factor Uncertainty ^a		Combined Uncertainty		Combined Uncertainty as % of TOTAL		
		Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	
		kt CO ₂ eq	kt CO ₂ eq	%	%	%	%	%	%	%	%	
3.B.1	Agriculture – Manure Management	CH ₄	2 461	3 891	0.00	0.00	0.00	0.00	38.00	32.00	0.16	0.19
	Agriculture – Total N ₂ O	N ₂ O	15 014	24 514	0.00	0.00	0.00	0.00	21.00	25.00	0.53	0.92
3.B.2	Agriculture – Manure Management Direct Emissions	N ₂ O	3 042	3 290	0.00	0.00	0.00	0.00	51.00	51.00	0.26	0.25
3.B.2	Agriculture – Manure Management Indirect Emissions	N ₂ O	584	611	0.00	0.00	0.00	0.00	100.00	100.00	0.10	0.09
3.D.1	Agriculture – Direct Agriculture Soils	N ₂ O	8 775	16 407	0.00	0.00	0.00	0.00	34.00	34.00	0.50	0.83
3.D.2	Agriculture – Indirect Agriculture Soils	N ₂ O	2 560	4 194	0.00	0.00	0.00	0.00	100.00	100.00	0.43	0.62
3.F	Agriculture – Field Burning of Agricultural Residues	CH ₄	170	41	50.00	50.00	40.00	40.00	64.00	64.00	0.02	0.00
3.F	Agriculture – Field Burning of Agricultural Residues	N ₂ O	53	13	50.00	50.00	48.00	48.00	69.00	69.00	0.01	0.00
	Agriculture – Total CO ₂	CO ₂	1 191	3 037	0.00	0.00	0.00	0.00	38.00	44.00	0.08	0.20
3.G.1	Agriculture – Limestone CaCO ₃	CO ₂	385	171	30.00	30.00	50.00	50.00	58.00	58.00	0.04	0.01
3.H	Agriculture – Urea Application	CO ₂	754	2 521	15.00	15.00	50.00	50.00	52.00	52.00	0.07	0.20
3.I	Agriculture – Other Carbon-Containing Fertilizers	CO ₂	52	344	15.00	15.00	50.00	50.00	52.00	52.00	0.00	0.03
5.A.1	Solid Waste Disposal – Managed Waste Disposal Sites	CH ₄	19 590	22 135	59.00	59.00	46.00	46.00	76.00	76.00	2.49	2.49
5.A.2	Solid Waste Disposal – Unmanaged Waste Disposal Sites – Wood Waste Landfills	CH ₄	2 869	2 178	0.00	0.00	0.00	0.00	190.00	190.00	0.92	0.62
5.B.1	Biological Treatment of Solid Waste – Composting	CH ₄	34	154	0.00	0.00	63.00	88.00	63.00	88.00	0.00	0.02
5.B.1	Biological Treatment of Solid Waste – Composting	N ₂ O	39	180	0.00	0.00	53.00	60.00	53.00	60.00	0.00	0.02
5.B.2	Biological Treatment of Solid Waste – Aerobic Digestion – Industrial & Municipal Facilities	CH ₄	-	24	0.00	0.00	79.00	79.00	79.00	79.00	0.00	0.00
5.C.1	Incineration and Open Burning of Waste – Waste Incineration	CO ₂	179	84	4.00	4.40	32.00	35.00	36.00	36.00	0.01	0.00
5.C.1	Incineration and Open Burning of Waste – Waste Incineration	CH ₄	2	1	3.90	4.90	79.00	97.00	49.00	58.00	0.00	0.00
5.C.1	Incineration and Open Burning of Waste – Waste Incineration	N ₂ O	92	79	3.50	4.20	70.00	84.00	70.00	84.00	0.01	0.01
5.D	Wastewater Treatment and Discharge	CH ₄	781	1 052	43.00	43.00	36.00	36.00	55.00	55.00	0.07	0.09
5.D	Wastewater Treatment and Discharge	N ₂ O	798	1 419	10.00	10.00	50.00	50.00	51.00	51.00	0.07	0.11
5.D	Wastewater Treatment and Discharge	CO ₂	32	37	-	-	-	-	-	-	0.00	0.00

Notes:

- a. For categories where individual values are not given for emission factor and activity data uncertainty, combined uncertainty estimates are based on sectoral Monte Carlo analyses. For further information on sources of uncertainty data and calculation methods – as related to categories in the Energy, Industrial Processes and Product Use, and Waste sectors – the reader is referred to uncertainty sections in respective NIR chapters. In the case of Agriculture, emission factor uncertainty was back calculated from combined uncertainty from Monte Carlo analysis carried out for N₂O and CH₄ separately and total contribution to uncertainty is the summation of uncertainty from Monte Carlo analysis of N₂O and CH₄, combined with error propagation calculations for CO₂. For IPPU categories where the uncertainty values for activity data and emission factor are not provided, the combined uncertainty value is calculated using many subcategory inputs which have varying activity data and emission factor uncertainty values.
- b. 1.A.2.g.vii., 1.A.3.e.ii., 1.A.4.a.ii., 1.A.4.b.ii., 1.A.4.c.ii

Table A2–2 Uncertainty Assessment Level for base year and latest year with Land Use, Land-Use Change and Forestry

IPCC Source Category	Gas	Emissions		Activity Data Uncertainty ^a		Emission Factor Uncertainty ^a		Combined Uncertainty		Combined Uncertainty as % of TOTAL		
		Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	
		kt CO ₂ eq	kt CO ₂ eq	%	%	%	%	%	%	%	%	
TOTALS		531 185	665 655	2.40	2.00	1.90	1.80	14.00	8.00			
1.A.1.a	Fuel Combustion – Public Electricity and Heat Production	CO ₂	93 982	61 580	5.30	0.47	0.49	4.20	5.30	4.20	0.93	0.39
1.A.1.a	Fuel Combustion – Public Electricity and Heat Production	CH ₄	44	160	0.68	0.68	28.00	28.00	28.00	28.00	0.00	0.01
1.A.1.a	Fuel Combustion – Public Electricity and Heat Production	N ₂ O	492	391	0.48	0.48	180.00	180.00	180.00	180.00	0.17	0.11
1.A.1.b	Fuel Combustion – Petroleum Refining	CO ₂	17 300	14 386	0.93	0.92	8.80	8.80	8.80	8.90	0.29	0.19
1.A.1.b	Fuel Combustion – Petroleum Refining	CH ₄	11	8	0.81	0.81	200.00	200.00	200.00	200.00	0.00	0.00
1.A.1.b	Fuel Combustion – Petroleum Refining	N ₂ O	50	32	0.68	0.68	310.00	310.00	310.00	310.00	0.03	0.02
1.A.1.c	Fuel Combustion – Manufacture of Solid Fuels and Other Energy Industries	CO ₂	29 583	97 504	3.00	0.86	0.84	2.40	3.10	2.50	0.17	0.37
1.A.1.c	Fuel Combustion – Manufacture of Solid Fuels and Other Energy Industries	CH ₄	1 465	2 338	1.00	1.00	120.00	120.00	120.00	120.00	0.33	0.42
1.A.1.c	Fuel Combustion – Manufacture of Solid Fuels and Other Energy Industries	N ₂ O	197	574	0.93	0.93	440.00	440.00	440.00	440.00	0.16	0.38
1.A.2	Fuel Combustion – Manufacturing Industries and Construction	CO ₂	61 664	45 029	2.30	2.60	3.60	3.50	3.80	3.90	0.44	0.26
1.A.2	Fuel Combustion – Manufacturing Industries and Construction	CH ₄	64	62	2.60	2.60	26.00	26.00	26.00	26.00	0.00	0.00
1.A.2	Fuel Combustion – Manufacturing Industries and Construction	N ₂ O	483	480	2.70	2.70	41.00	41.00	41.00	41.00	0.04	0.03
1.A.2-3-42	Fuel Combustion -Off-Road ^b	CO ₂	35 295	33 887	1.20	1.10	0.13	0.11	1.20	1.10	0.08	0.06
1.A.2-3-42	Fuel Combustion -Off-Road ^b	CH ₄	1 288	499	1.60	1.10	32.00	11.00	32.00	11.00	0.08	0.01
1.A.2-3-42	Fuel Combustion -Off-Road ^b	N ₂ O	118	467	0.97	1.80	280.00	68.00	280.00	68.00	0.06	0.05
1.A.3.a	Fuel Combustion – Civil Aviation	CO ₂	7 203	4 578	0.79	0.77	0.47	0.41	0.92	0.87	0.01	0.01
1.A.3.a	Fuel Combustion – Civil Aviation	CH ₄	11	4	0.80	0.77	220.00	220.00	220.00	220.00	0.00	0.00
1.A.3.a	Fuel Combustion – Civil Aviation	N ₂ O	67	40	0.72	0.72	650.00	650.00	650.00	650.00	0.08	0.04
1.A.3.b	Fuel Combustion – Road Transportation	CO ₂	80 538	128 784	0.80	1.20	0.10	0.13	0.81	1.20	0.12	0.24
1.A.3.b	Fuel Combustion – Road Transportation	CH ₄	308	207	0.78	1.10	14.00	110.00	14.00	110.00	0.01	0.03
1.A.3.b	Fuel Combustion – Road Transportation	N ₂ O	2 923	2 250	1.20	1.30	33.00	41.00	33.00	41.00	0.18	0.14
1.A.3.c	Fuel Combustion – Railways	CO ₂	6 200	6 408	3.00	3.00	0.28	0.28	3.00	3.00	0.04	0.03
1.A.3.c	Fuel Combustion – Railways	CH ₄	9	9	3.00	3.10	150.00	150.00	150.00	150.00	0.00	0.00
1.A.3.c	Fuel Combustion – Railways	N ₂ O	709	750	3.00	3.10	200.00	200.00	200.00	200.00	0.27	0.22
1.A.3.d	Fuel Combustion – Navigation	CO ₂	2 149	3 810	2.10	2.70	1.70	0.39	2.80	2.70	0.01	0.02
1.A.3.d	Fuel Combustion – Navigation	CH ₄	5	9	2.10	2.80	36.00	45.00	36.00	45.00	0.00	0.00
1.A.3.d	Fuel Combustion – Navigation	N ₂ O	17	31	2.10	2.80	100.00	130.00	100.00	130.00	0.00	0.01
1.A.3.e	Fuel Combustion – Pipeline Transport	CO ₂	6 685	7 494	0.99	0.99	0.71	0.90	1.20	1.30	0.02	0.02
1.A.3.e	Fuel Combustion – Pipeline Transport	CH ₄	167	182	1.00	1.00	15.00	15.00	15.00	15.00	0.00	0.00
1.A.3.e	Fuel Combustion – Pipeline Transport	N ₂ O	53	57	1.00	1.00	490.00	490.00	490.00	490.00	0.05	0.04
1.A.4	Fuel Combustion – Other Sectors	CO ₂	69 527	75 339	1.40	2.00	1.90	1.50	2.00	2.20	0.27	0.25
1.A.4	Fuel Combustion – Other Sectors	CH ₄	2 206	1 357	5.70	5.70	16.00	16.00	16.00	16.00	0.07	0.03
1.A.4	Fuel Combustion – Other Sectors	N ₂ O	638	656	4.20	4.20	30.00	30.00	30.00	30.00	0.04	0.03
1.A.4.c.iii	Fuel Combustion – Fishing	CO ₂	866	230	11.00	3.70	1.00	0.35	11.00	3.70	0.02	0.00
1.A.4.c.iii	Fuel Combustion – Fishing	CH ₄	2	1	18.00	22.00	300.00	370.00	300.00	370.00	0.00	0.00
1.A.4.c.iii	Fuel Combustion – Fishing	N ₂ O	7	2	11.00	3.60	500.00	170.00	500.00	170.00	0.01	0.00
1.A.5.b.	Fuel Combustion – Other (Military Aviation)	CO ₂	231	185	0.62	0.64	0.31	0.32	0.69	0.72	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Aviation)	CH ₄	0	0	0.83	0.51	740.00	440.00	740.00	440.00	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Aviation)	N ₂ O	2	2	0.61	0.64	550.00	580.00	550.00	580.00	0.00	0.00

Table A2–2 Uncertainty Assessment Level for base year and latest year with Land Use, Land-Use Change and Forestry (cont'd)

IPCC Source Category		Gas	Emissions		Activity Data Uncertainty ^a		Emission Factor Uncertainty ^a		Combined Uncertainty		Combined Uncertainty as % of TOTAL	
			Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020
			kt CO ₂ eq	kt CO ₂ eq	%	%	%	%	%	%	%	%
1.A.5.b.	Fuel Combustion – Other (Military Navigation)	CO ₂	28	107	0.36	1.70	0.03	0.16	0.36	1.70	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Navigation)	CH ₄	0	0	0.58	11.00	9.80	170.00	9.80	170.00	0.00	0.00
1.A.5.b.	Fuel Combustion – Other (Military Navigation)	N ₂ O	0	1	0.35	1.80	16.00	78.00	16.00	78.00	0.00	0.00
1.B.1.a	Fugitive Sources – Coal Mining	CH ₄	2 824	1 068	0.00	0.00	0.00	0.00	57.00	57.00	0.30	0.09
1.B.2.(a+b)	Fugitive Sources – Oil & Gas	CO ₂	99	631	0.00	0.00	0.00	0.00	31.00	29.00	0.01	0.03
1.B.2.(a+b)	Fugitive Sources – Oil & Gas	CH ₄	18 787	19 740	0.00	0.00	0.00	0.00	6.00	8.00	0.21	0.24
1.B.2.(a+b)	Fugitive Sources – Oil & Gas	N ₂ O	30	91	0.00	0.00	0.00	0.00	300.00	300.00	0.02	0.04
1.B.2.c	Fugitive Sources – Venting	CO ₂	7 000	9 609	0.00	0.00	0.00	0.00	18.00	26.00	0.24	0.38
1.B.2.c	Fugitive Sources – Flaring	CO ₂	4 859	5 817	0.00	0.00	0.00	0.00	10.00	8.00	0.09	0.07
1.B.2.c	Fugitive Sources – Venting & Flaring	CH ₄	15 973	12 725	0.00	0.00	0.00	0.00	7.00	5.00	0.21	0.10
1.B.2.c	Fugitive Sources – Venting & Flaring	N ₂ O	2	7	0.00	0.00	0.00	0.00	54.00	120.00	0.00	0.00
1.C	CO ₂ Transport and Storage	CO ₂	-	0	0.00	2.00	0.00	100.00	0.00	100.00	0.00	0.00
2.A.1	IPPU – Cement Production	CO ₂	5 823	6 625	0.00	0.00	0.00	0.00	14.00	8.50	0.00	0.00
2.A.2	IPPU – Lime Production	CO ₂	1 806	1 193	36.00	8.00	2.00	2.00	31.00	6.70	0.00	0.00
2.A.3	IPPU – Glass Production	CO ₂	166	43	0.00	0.00	0.00	0.00	14.00	10.00	0.00	0.00
2.A.4.b	IPPU – Other Uses of Soda Ash	CO ₂	100	46	0.00	0.00	0.00	0.00	7.50	6.00	0.00	0.00
2.A.4.c	IPPU – Other (Magnesite Use)	CO ₂	147	116	5.50	7.80	2.00	2.10	5.80	8.10	0.00	0.00
2.A.4.d	IPPU – Other (Limestone and Dolomite Use)	CO ₂	449	98	0.00	0.00	0.00	0.00	32.00	32.00	0.00	0.00
2.B.1	IPPU – Ammonia Production	CO ₂	2 754	2 467	2.20	1.40	9.00	10.00	6.70	6.90	0.00	0.00
2.B.2	IPPU – Nitric Acid Production	N ₂ O	973	189	2.00	2.00	10.00	10.00	2.20	1.10	0.00	0.00
2.B.3	IPPU – Adipic Acid Production	N ₂ O	10 303	0	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00
2.B.7	IPPU – Soda Ash Production	CO ₂	-	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.B.8	IPPU – Petrochemical and Carbon Black Production	CO ₂	3 367	3 776	0.00	0.00	0.00	0.00	4.20	3.10	0.00	0.00
2.B.8	IPPU – Petrochemical and Carbon Black Production (including carbide production)	CH ₄	134	141	0.00	0.00	0.00	0.00	13.00	17.00	0.00	0.00
2.B.8	IPPU – Petrochemical and Carbon Black Production	N ₂ O	15	13	0.00	0.00	0.00	0.00	8.10	10.00	0.00	0.00
2.B.9.a	IPPU – Fluorochemical Production	HFCs	971	0	0.00	0.00	0.00	0.00	50.00	0.00	0.09	0.00
2.C.1	IPPU – Iron and Steel Production	CO ₂	10 478	6 984	0.00	0.00	0.00	0.00	5.50	5.60	0.00	0.00
2.C.1	IPPU – Iron and Steel Production	CH ₄	2	2	0.00	0.00	0.00	0.00	410.00	410.00	0.00	0.00
2.C.3	IPPU – Aluminium Production	CO ₂	2 715	5 131	0.00	0.00	0.00	0.00	15.00	7.10	0.00	0.00
2.C.3	IPPU – Aluminium Production	PFCs	7 558	770	0.00	0.00	0.00	0.00	18.00	9.10	0.00	0.00
2.C.3	IPPU – Aluminium Production	SF ₆	56	1	0.00	0.00	0.00	0.00	1.00	3.30	0.00	0.00
2.C.4	IPPU – Magnesium Production	SF ₆	2 738	0	0.00	0.00	0.00	0.00	4.20	0.00	0.00	0.00
2.C.7	IPPU – Other (Magnesium Casting)	SF ₆	225	102	0.00	0.00	0.00	0.00	4.40	6.40	0.00	0.00
2.D.3.a	IPPU – Non-Energy Products from Fuels and Solvent Use Other – Other (Other and Undifferentiated)	CO ₂	5 804	9 881	0.00	0.00	0.00	0.00	29.00	20.00	0.00	0.00
2.D.3.b	IPPU – Non-Energy Products from Fuels and Solvent Use Other – Other (Use of Urea in SCR Vehicles)	CO ₂	-	28	0.00	0.00	0.00	0.00	50.00	50.00	0.00	0.00
2.E.1	IPPU – Integrated Circuit or Semiconductor	PFCs	0	11	250.00	2.00	200.00	19.00	320.00	19.00	0.00	0.00
2.E.1	IPPU – Integrated Circuit or Semiconductor	SF ₆	4	35	15.00	15.00	30.00	30.00	45.00	45.00	0.00	0.00
2.E.1	IPPU – Integrated Circuit or Semiconductor	NF ₃	0	1	250.00	2.00	70.00	300.00	260.00	300.00	0.00	0.00
2.E.5	IPPU – Other Emissive Applications	PFCs	-	0	0.00	2.00	0.00	50.00	0.00	50.00	0.00	0.00
2.F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	HFCs	-	11 944	0.00	0.00	0.00	0.00	11.00	0.00	0.00	0.00
2.F	IPPU – Product Uses as Substitutes for Ozone Depleting Substances	PFCs	-	9	0.00	0.00	0.00	0.00	0.00	23.00	0.00	0.00
2.G.1	IPPU – Electrical Equipment	SF ₆	202	165	11.00	11.00	30.00	30.00	32.00	32.00	0.00	0.00
2.G.3.a	IPPU – Other (Medical Applications of N ₂ O)	N ₂ O	146	454	20.00	20.00	5.00	5.00	18.00	20.00	0.00	0.00
2.G.3.b	IPPU – Other (Uses of N ₂ O for Propellant)	N ₂ O	26	83	20.00	20.00	5.00	5.00	18.00	20.00	0.00	0.00
2.G.4	IPPU – Other Contained Product Uses	PFCs	-	24	0.00	2.00	0.00	50.00	0.00	51.00	0.00	0.00

Table A2–2 Uncertainty Assessment Level for base year and latest year with Land Use, Land-Use Change and Forestry (cont'd)

IPCC Source Category	Gas	Emissions		Activity Data Uncertainty ^a		Emission Factor Uncertainty ^a		Combined Uncertainty		Combined Uncertainty as % of TOTAL		
		Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	Base Year	2020	
		kt CO ₂ eq	kt CO ₂ eq	%	%	%	%	%	%	%	%	
	Agriculture – Total CH ₄	CH ₄	24 978	27 608	0.00	0.00	0.00	0.00	20.00	19.00	0.94	0.80
3.A	Agriculture – Enteric Fermentation	CH ₄	22 347	23 677	0.00	0.00	0.00	0.00	22.00	22.00	0.93	0.78
3.B.1	Agriculture – Manure Management	CH ₄	2 461	3 891	0.00	0.00	0.00	0.00	38.00	32.00	0.18	0.19
	Agriculture – Total N ₂ O	N ₂ O	15 014	24 514	0.00	0.00	0.00	0.00	21.00	25.00	0.60	0.93
3.B.2	Agriculture – Manure Management Direct Emissions	N ₂ O	3 042	3 290	0.00	0.00	0.00	0.00	51.00	51.00	0.29	0.25
3.B.2	Agriculture – Manure Management Indirect Emissions	N ₂ O	584	611	0.00	0.00	0.00	0.00	100.00	100.00	0.11	0.09
3.D.1	Agriculture – Direct Agriculture Soils	N ₂ O	8 775	16 407	0.00	0.00	0.00	0.00	34.00	34.00	0.56	0.84
3.D.2	Agriculture – Indirect Agriculture Soils	N ₂ O	2 560	4 194	0.00	0.00	0.00	0.00	100.00	100.00	0.48	0.63
3.F	Agriculture – Field Burning of Agricultural Residues	CH ₄	170	41	50.00	50.00	40.00	40.00	64.00	64.00	0.02	0.00
3.F	Agriculture – Field Burning of Agricultural Residues	N ₂ O	53	13	50.00	50.00	48.00	48.00	69.00	69.00	0.01	0.00
	Agriculture – Total CO ₂	CO ₂	1 191	3 037	0.00	0.00	0.00	0.00	38.00	44.00	0.09	0.20
3.G.1	Agriculture – Limestone CaCO ₃	CO ₂	385	171	30.00	30.00	50.00	50.00	58.00	58.00	0.04	0.02
3.H	Agriculture – Urea Application	CO ₂	754	2 521	15.00	15.00	50.00	50.00	52.00	52.00	0.07	0.20
3.I	Agriculture – Other Carbon-Containing Fertilizers	CO ₂	52	344	15.00	15.00	50.00	50.00	52.00	52.00	0.01	0.03
4.A.1	LULUCF – Forest Land Remaining Forest Land	CO ₂	(201 515)	(130 438)	0.00	0.00	0.00	0.00	33.00	37.00	-12.48	-7.21
4.A.1	LULUCF – Forest Land Remaining Forest Land	CH ₄	442	277	0.00	0.00	0.00	0.00	43.00	150.00	0.04	0.06
4.A.1	LULUCF – Forest Land Remaining Forest Land	N ₂ O	223	180	0.00	0.00	0.00	0.00	43.00	150.00	0.02	0.04
4.A.2	LULUCF – Land Converted to Forest Land	CO ₂	(1 069)	(241)	0.00	0.00	0.00	0.00	40.00	110.00	-0.08	-0.04
4.B	LULUCF – Cropland	CO ₂	(9 020)	(14 738)	0.00	0.00	0.00	0.00	22.00	23.00	-0.37	-0.51
4.B	LULUCF – Cropland	N ₂ O	11	3	0.00	0.00	0.00	0.00	40.00	40.00	0.00	0.00
4.C	LULUCF – Grassland	CH ₄	0	1	0.00	0.00	0.00	0.00	64.00	64.00	0.00	0.00
4.C	LULUCF – Grassland	N ₂ O	0	0	0.00	0.00	0.00	0.00	69.00	69.00	0.00	0.00
4.D	LULUCF – Wetlands	CO ₂	2 498	1 814	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.D	LULUCF – Wetlands	CH ₄	6	15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.D	LULUCF – Wetlands	N ₂ O	2	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.E	LULUCF – Settlements	CO ₂	(4 175)	(4 403)	0.00	0.00	0.00	0.00	28.00	28.00	-0.22	-0.19
4.F	LULUCF – Conversion of Forest Land	CO ₂	17 687	12 429	0.00	0.00	0.00	0.00	12.00	17.00	0.42	0.32
4.F	LULUCF – Conversion of Forest Land	CH ₄	445	244	0.00	0.00	0.00	0.00	28.00	25.00	0.02	0.01
4.F	LULUCF – Conversion of Forest Land	N ₂ O	221	124	0.00	0.00	0.00	0.00	28.00	25.00	0.01	0.00
4.G	LULUCF – Harvested Wood Products (HWP)	CO ₂	130 706	127 971	0.00	0.00	0.00	0.00	16.00	6.40	3.98	1.22
5.A.1	Solid Waste Disposal – Managed Waste Disposal Sites	CH ₄	19 590	22 135	59.00	59.00	46.00	46.00	76.00	76.00	2.78	2.51
5.A.2	Solid Waste Disposal – Unmanaged Waste Disposal Sites – Wood Waste Landfills	CH ₄	2 869	2 178	0.00	0.00	0.00	0.00	190.00	190.00	1.03	0.62
5.B.1	Biological Treatment of Solid Waste – Composting	CH ₄	34	154	0.00	0.00	63.00	88.00	63.00	88.00	0.00	0.02
5.B.1	Biological Treatment of Solid Waste – Composting	N ₂ O	39	180	0.00	0.00	53.00	60.00	53.00	60.00	0.00	0.02
5.B.2	Biological Treatment of Solid Waste – Aerobic Digestion – Industrial & Municipal Facilities	CH ₄	-	24	0.00	0.00	79.00	79.00	79.00	79.00	0.00	0.00
5.C.1	Incineration and Open Burning of Waste – Waste Incineration	CO ₂	179	84	4.00	4.40	32.00	35.00	36.00	36.00	0.01	0.00
5.C.1	Incineration and Open Burning of Waste – Waste Incineration	CH ₄	2	1	3.90	4.90	79.00	97.00	49.00	58.00	0.00	0.00
5.C.1	Incineration and Open Burning of Waste – Waste Incineration	N ₂ O	92	79	3.50	4.20	70.00	84.00	70.00	84.00	0.01	0.01
5.D	Wastewater Treatment and Discharge	CH ₄	781	1 052	43.00	43.00	36.00	36.00	55.00	55.00	0.08	0.09
5.D	Wastewater Treatment and Discharge	N ₂ O	798	1 419	10.00	10.00	50.00	50.00	51.00	51.00	0.08	0.11
5.D	Wastewater Treatment and Discharge	CO ₂	32	37	-	-	-	-	-	-	0.00	0.00

Notes:

- a. For categories where individual values are not given for emission factor and activity data uncertainty, combined uncertainty estimates are based on sectoral Monte Carlo analyses. For further information on sources of uncertainty data and calculation methods – as related to categories in the Energy, Industrial Processes and Product Use, and Waste sectors – the reader is referred to uncertainty sections in respective NIR chapters. In the case of Agriculture, emission factor uncertainty was back calculated from combined uncertainty from Monte Carlo analysis carried out for N₂O and CH₄ separately and total contribution to uncertainty is the summation of uncertainty from Monte Carlo analysis of N₂O and CH₄, combined with error propagation calculations for CO₂. For IPPU categories where the uncertainty values for activity data and emission factor are not provided, the combined uncertainty value is calculated using many subcategory inputs which have varying activity data and emission factor uncertainty values.
- b. 1.A.2.g.vii, 1.A.3.e.ii, 1.A.4.a.ii, 1.A.4.b.ii, 1.A.4.c.ii

ANNEX 3

METHODOLOGIES

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A3.1. Methodology and Data for Estimating Emissions from Fossil Fuel Combustion

The following presents an overview of the methodology, activity data and emission factors used to estimate CO₂, CH₄ and N₂O emissions from fuel combustion sources for the Energy sector.

A3.1.1. Methodology

In general, estimating greenhouse gas (GHG) emissions from fuel combustion activities uses a top-down method, following the Tier 3 and Tier 2 sectoral approach from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). As illustrated by Equation A3.1–1, to calculate the emission for each source category, the quantity of fuel at the national, provincial and territorial level is multiplied by the corresponding fuel-specific emission factor. Sections A3.1.4.1 and A3.1.4.2 discuss refinements and deviations from the general approach to estimating combustion emissions for the stationary combustion and transport sections, respectively. The purpose of these refinements is to increase the accuracy and allocation of the emissions associated with each source category when additional details or parameters are available. The Energy chapter (Chapter 3) of this report discusses specific methodological issues.

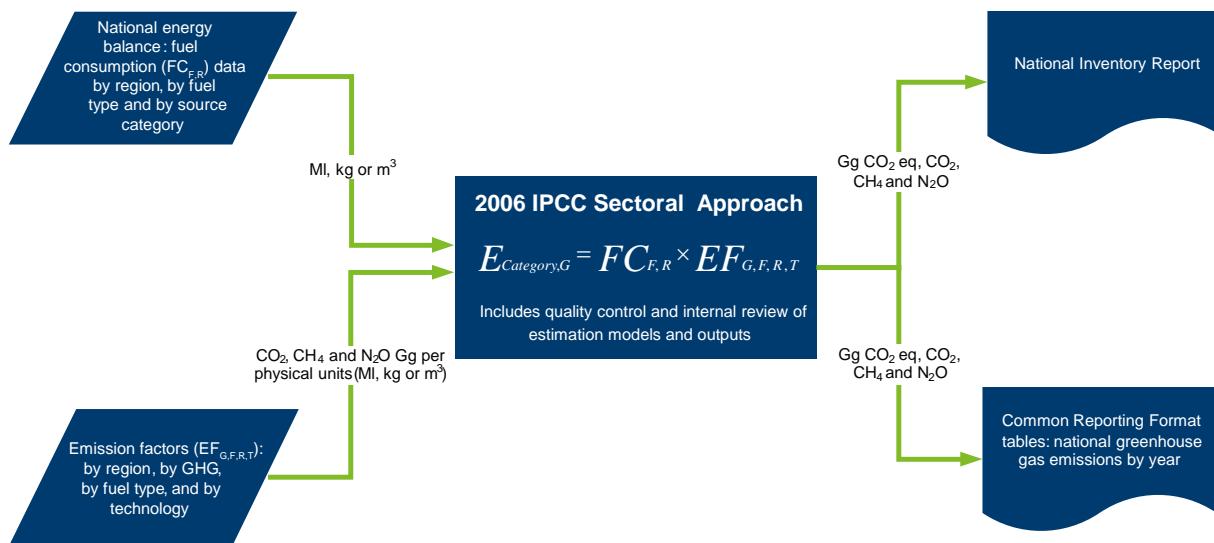
Equation A3.1–1 for general fuel combustion

$$E_{Category,G} = FC_{E,R} * EF_{G,E,R,T}$$

$E_{Category,G}$	=	GHG emissions by source category and by GHG (CO ₂ , CH ₄ or N ₂ O)
$FC_{E,R}$	=	quantity of fuel consumed (in physical units, such as kg, L, or m ³) by fuel type (i.e. natural gas, sub-bituminous coal, kerosene, etc.) and by region
$EF_{G,E,R,T}$	=	country-specific emission factor (in physical units) by GHG, by fuel type, by region (where available) and by technology (for non-CO ₂ factors)

The stationary combustion and transport models primarily use relational databases to process the national-, provincial- and territorial- activity data and emission factors used to estimate GHG emissions (Figure A3.1–1). Statistics Canada prepares the national energy balance using data reported in physical units by the producing and consuming sectors. For this reason, the physical units were judged the most accurate for generating emission estimates. Country-specific emission factors, as applied, are in physical units to minimize the number of additional conversion factors and thus limit the uncertainty associated with estimates. The uncertainty of estimates are further reduced by applying available higher-resolution emission factors at the provincial and territorial level rather than the national level (e.g. regional coal and natural gas emission factors are used to account for the variation in carbon content). Non-CO₂ emission factors address any existing combustion technology differences.

Figure A3.1-1 GHG Estimation Process Flow



A3.1.2. Activity Data from Statistics Canada

The principal source of fuel and energy data used to estimate combustion emissions is the annual *Report on Energy Supply and Demand in Canada* (RESD) (Statistics Canada, 1990–), also referred to as the national energy balance. The RESD uses both top-down and bottom-up approaches to estimate the supply of, and demand for, energy in Canada. The production of fuels in Canada is balanced with the use of fuels in broad categories such as import/export, producer consumption, residential, and industry. Industrial energy-use data is allocated using the North American Industrial Classification System (NAICS). Currently, the RESD reports energy used to generate electricity or steam by industry (auto producers) in two separate lines (one for electricity and one for steam), without any further disaggregation by industrial subcategories. Prior to 1998, the *Industrial Consumption of Energy Survey* (ICE) (Statistics Canada, no date[a]) provided these summary line quantities. From 1998 on, the electricity line (from auto producers) is based on the quantities reported in the *Electric Power Thermal Generating Station Fuel Consumption Survey* (EPTGS) (Statistics Canada, no date[b]). Statistics Canada implemented this improvement to increase the transparency and accuracy of subsector information, since the fuel used to generate electricity is more complete and of higher quality. The steam line continues to be populated using the ICE data.

While the RESD provides fuel use data at a provincial and territorial level, the accuracy of these data is generally not as high as that of the national data. Statistics Canada typically allocates final fuel demand by subcategories for the RESD through a number of surveys directed at producers and suppliers of energy, provincial and territorial energy ministries and some users of energy. The accuracy following these allocations is less than that of the total available energy supply at the national level. As a result, the total emission estimates for Canada are more certain than the emissions from specific subcategories. Since 1995, Statistics Canada has been collecting energy statistics directly from end users through the annual ICE survey. Estimating fuel use by industry using a bottom-up approach provides more accurate subcategory information. Refer to Annex 4, National Energy Balance, for additional discussion on the development of the RESD and the ICE data set, including a discussion of Statistics Canada's quality assurance / quality control activities. Sector-specific surveys provide verification of sector trends and emissions allocation.

The combustion and transport models apply the quantity of fossil fuel consumed in physical units rather than in energy units, since this is how Statistics Canada collects data from reporting facilities under the *Statistics Act*. The quantities of fossil fuel consumed are also available in gross calorific units; however, as discussed, this is assumed to be less accurate. When converting to energy values, with the exception of natural gas, Statistics Canada applies constant energy conversion factors (a factor for 1990 to 1997 and another factor for 1998 onward) to each fuel type without taking into account year-to-year variability in fuels such as coal, petroleum coke and refinery fuel gas (still gas). These energy conversion factors are applied for the reporting of fuel quantities in the common reporting format (CRF) tables, and nationally weighted values were determined for reference approach calculations (refer to Table A4-2 for details). One exception involves waste fuels, for which the data are only available in energy units from the Cement Association of Canada. Statistics Canada and Environment and Climate Change Canada (ECCC) have initiated a multi-year work program to better track and update energy conversion factors. Refer to the Planned Improvement section of Chapter 3 for further details.

Additional non-Statistics Canada data sources used by the combustion and transport models, such as landfill gas quantities, waste fuel consumption and vehicle fleet information, are included in the specific methodological discussions (sections A3.1.4.1 and A3.1.4.2).

A3.1.3. Fuel Combustion Emission and Oxidation Factors

The following is a brief summary of the emission factors for fuels that are the largest contributors to Canadian GHG emissions. A detailed description of emission factors used in the current fossil fuel combustion models can be found in Annex 6.

Natural Gas: The emission factors for CO₂ vary depending on the source of natural gas and whether the product is marketable or non-marketable (raw natural gas for on-site consumption by natural gas producers). Therefore, provinces and territories have varying emission factors based on yearly natural gas supplied and its hydrocarbon composition. The emission factors for CH₄ and N₂O vary with the combustion technology.

Refined Petroleum Products (RPP): Refined petroleum products include, but are not limited to, fuels such as diesel, gasoline, light fuel oil and heavy fuel oil. The emission factors vary with fuel type and/or combustion technology (for CH₄ and N₂O).

Coal: The CO₂ emission factors vary by the coal properties, province of use and coal origin, whether domestic or foreign. The emission factors for CH₄ and N₂O vary by the combustion technology.

The Intergovernmental Panel on Climate Change (IPCC) default oxidation value applies to all fuels except coal, where country-specific oxidation factors applied at the provincial and territorial level reflect regional variations in combustion efficiencies. Refer to the Recalculation section of Chapter 3 and Annex 6 for more detail on coal oxidation factors.

A3.1.3.1. CO₂ Emission Factors

CO₂ emissions from fuel combustion activities depend on the amount of fuel consumed, the carbon content of the fuel and the applied oxidation factor. The applied emission factors vary by fuel type and by region, where applicable. There is discussion of CO₂ emission factor derivation in Annex 6, in *Fossil Fuel and Derivative Factors* (McCann, 2000), in *Updated CO₂ Emission Factors for Gasoline and Diesel Fuel* (ECCC, 2017b) and in *Updated Carbon Dioxide Emission Factors for Coal Combustion* (ECCC, 2019). Fuel properties, such as carbon content, density and heating value, were determined using accepted industrial testing standards from the American Society for Testing and Materials (ASTM) and the Canadian General Standards Board (CGSB).

The waste fuel emission factor is based on energy content since activity data reported by the Cement Association of Canada are in energy units.

A3.1.3.2. Non-CO₂ Emission Factors

Emission factors for all non-CO₂ GHGs from combustion activities vary to a greater or lesser degree with:

- fuel type
- technology
- operating conditions
- maintenance and vintage of technology

During the combustion of carbon-based fuels, a small portion of the fuel remains unoxidized as CH₄. Additional research is needed to better establish CH₄ emission factors for many combustion processes. Overall factors were developed for sectors based on typical technologies and available emission factors.

During combustion, some of the nitrogen in the fuel and air is converted to N₂O. The production of N₂O is dependent on the combustion temperature and the emission control technology employed. Additional research is needed to better establish N₂O emission factors for many combustion processes. Overall factors were developed for sectors based on typical technologies and available emission factors. Annex 6 lists non-CO₂ emission factors used in this inventory.

A3.1.4. Methodology for Stationary Combustion and Transport

This section discusses methods used to calculate and report emissions associated with the Energy sector, and specifically stationary combustion and transport.

For reporting under the United Nations Framework Convention on Climate Change (UNFCCC), CO₂ emissions from biomass fuels (including landfill gas) are not to be included in the Energy sector total. The Land Use, Land-Use Change and Forestry (LULUCF) sector accounts for CO₂ emissions from biomass fuel combustion as a loss of biomass (forest) stocks. CO₂ emissions from biomass combustion for energy use is a memo item in the UNFCCC's Common Reporting Format (CRF) tables and is provided for information purposes. The Energy sector reports CH₄ and N₂O emissions from biomass fuel combustion in the appropriate subcategories and includes it in the inventory totals.

A3.1.4.1. Stationary Combustion

The methodology used to estimate GHG emissions from stationary fuel combustion is consistent with the IPCC Tier 2 sectoral approach, along with country-specific emission factors as outlined in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). The Industrial Processes and Product Use sector (Annex 3.3) presents the methodology for calculating SF₆ emissions from electrical transmission systems.

Emission calculations use nationally reported activity data, except when emission factors are available at the provincial and territorial level. In these instances, the national total is the aggregated sum of the provincial and territorial emissions.

Emission estimates are calculated using Equation A3.1–1 exclusively.

Table A3.1–1 presents activity data sources used in the stationary combustion model methodology. The data provided to ECCC is in electronic format and may differ slightly when compared with Statistics Canada's published values, which are rounded.

Much of the stationary combustion model's complexity lies in the reallocation of data presented in the RESD in order to comply with the requirements of IPCC categories and UNFCCC CRF reporting tables. In addition, in keeping with the 2006 IPCC Guidelines, the allocation of all fuel types uses the CRF fuel grouping (solid, liquid, gaseous, biomass and other) (see Table A4–2 in Annex 4).

Combined Heat and Power Allocation

Activity data, in the form of fuel used by utilities, are currently aggregated to two summary lines in the RESD (Electricity by Utilities and Steam Generation), representing, electricity generation, and combined heat and power facilities. In addition, solid wood waste and spent pulping liquor used by utilities are allocated to Table 10 – Consumption of Solid Wood Waste and Spent Pulping Liquor for Energy Production.

Since the Electricity by Utilities line (RES Line 10) is populated with EPTGS survey data, the reallocation was completed using fractions developed using the quantities reported by the Electricity Generation subcategory in the EPTGS survey. For each fuel and each province and territory, the fuel use data reported in the EPTGS, along with a listing of facilities that are combined heat and power facilities (generated by ECCC), are used to develop the combined heat and power fraction of the total fuel use. The fractions are then used with RES Line 10 to determine what portion of that line should be reallocated to combined heat and power. The remainder is allocated to electricity generation.

The solid wood waste and spent pulping liquor allocation are discussed below.

Table A3.1–1 Activity Data Model References

Statistics Canada. 1990. *Report on energy supply and demand in Canada*. Annual report. Catalogue no. 57-003-X.

Waste fuel data – Based on CEECD. CEECD database on energy, production and intensity indicators for Canadian industry. NAICS 327310 Cement Manufacturing. Canadian Energy and Emissions Data Centre.

Environment and Climate Change Canada. 2020. *Residential Fuelwood Consumption in Canada*. Unpublished report. Prepared by Kay J., Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.

Environment and Climate Change Canada. 2020. Landfill Gas Utilization and Waste Incineration, National Inventory Report, Section A3.6: Methodology for Waste Sector.

Electricity by Industry Allocation

Activity data, in the form of fuel used by industry (including Petroleum Refining) to generate electricity or steam, are currently aggregated to two summary lines in the RESD (Electricity by Industry and Steam Generation). In addition, solid wood waste and spent pulping liquor used by industry are allocated to Table 10 – Consumption of Solid Wood Waste and Spent Pulping Liquor for Energy Production.

The Electricity by Industry line (RES Line 11) is populated with EPTGS survey data. The reallocation of RESD Line 11 values from 1998 to present was completed using fractions developed based on the quantities reported by the Electricity Generation subcategory in the EPTGS survey, as follows:

- For each fuel and each province and territory, the fuel use data reported by industry in the EPTGS for electricity generation are used to develop each industry's fraction of the total fuel use.
- The fractions are then used with RESD Line 11 to determine what portion of that line should be reallocated to a particular industry.
- This portion is added to the activity data already reported for that industry.

The reallocation of RESD Line 11 values between 1990 and 1997 was completed using fractions developed using the quantities reported by the Electricity Generation subcategory in the ICE survey, since EPTGS data are not available prior to 1998.

- For each fuel and each province and territory, the fuel use data reported by industry in the ICE survey for electricity generation are used to develop each industry's fraction of the total fuel use.
- The fractions are then used with RESD Line 11 to determine what portion of that line should be reallocated to a particular industry.
- This portion is added to the activity data already reported for that industry.
- Since ICE data did not exist prior to 1995, for years between 1990 and 1995, the 1995 fractions were used.

Since the Steam Generation line (RES Line 14) is populated with ICE data, the procedure used to reallocate the RESD Line 11 values between 1990 and 1997 is also applied to the RESD Line 14 values (for all years) using corresponding ICE data representing steam generation by facilities falling under the Electricity Generation subcategory.

The solid wood waste and spent pulping liquor allocation is discussed below.

Solid Wood Waste and Spent Pulping Liquor Allocation

Activity data, in the form of solid wood waste and spent pulping liquor, are currently aggregated to a summary table in the RESD (Table 10 – Consumption of Solid Wood Waste and Spent Pulping Liquor for Energy Production).

The Solid Wood Waste and Spent Pulping Liquor table (RESD Table 10) is populated with ICE data. The procedure used to reallocate the RESD Line 11 values between 1990 and 1997 is also applied to the RESD Table 10 values (for all years) using corresponding ICE data representing solid wood waste and spent pulping liquor consumption by facilities falling under the Electricity Generation subcategory.

A3.1.4.1.1. Public Electricity and Heat Production (CRF Category 1.A.1.a)

The Public Electricity and Heat Production subcategory includes 1.A.1.a.i – Electricity Generation, 1.A.1.a.ii – Combined Heat and Power Generation, and 1.A.1.a.iii – Heat Plants. This subcategory should include all emissions from main activity producers (previously known as public utilities) of electricity generation, combined heat and power generation, and heat plants. Emissions from auto producers are allocated to their respective industrial subcategories.

Two lines in the RESD (one for electricity and one for steam) report activity data from this subcategory; however, they are summary lines and are not divided into electricity generation, combined heat and power, and heat plants. In addition, activity data, in the form of solid wood waste and spent pulping liquor, are currently aggregated to a summary table in the RESD (Table 10 – Consumption of Solid Wood Waste and Spent Pulping Liquor for Energy Production). The aggregated data need to be reallocated to the appropriate subcategory where the fuel is used. Section A3.1.4.1 provides a detailed discussion of the method used.

CO_2 , CH_4 and N_2O emissions are estimated by applying Equation A3.1–1 to activity data and emission factors for each specific fuel. As previously discussed, in order to obtain higher accuracy in GHG emissions, regional emission factors are applied to provincial and territorial data where available. For this sector, there are regional emission factors for coal and natural gas. For the remaining fuels, the emission factors are applied to the nationally reported data.

Table A3.1–2 Emission Estimation Methodology for Public Electricity and Heat Production

CRF Source Category ^a	Fuel Type ^b	Data Source		
		Publication ^c	Table	Line
1.A.1.a.i Electricity Generation	Solid Fuels	RES	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Utilities ^d Steam Generation ^d
	Liquid Fuels	RES	3 – Refined Petroleum Products	
	Gaseous Fuels	RES	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RES	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
1.A.1.a.ii Combined Heat and Power Generation	Solid Fuels	RES	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Utilities ^d Steam Generation ^d
	Liquid Fuels	RES	3 – Refined Petroleum Products	
	Gaseous Fuels	RES	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RES	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
1.A.1.a.iii Heat Plants	NO			

Notes:

NO = Not occurring

a. The CRF categories listed are the lowest-level subcategories for which emissions are estimated.

b. As outlined in IPCC (2006) (Volume 2, Table 1.1).

c. Publication references are provided in Table A3.1–1.

d. A portion of this data source is allocated to this CRF source category prior to calculating emissions.

Table A3.1–2 provides a summary of the methodology for the Public Electricity and Heat Production category.

A3.1.4.1.2. Petroleum Refining (CRF Category 1.A.1.b) and Manufacture of Solid Fuels and Other Energy Industries (CRF Category 1.A.1.c)

To meet the UNFCCC reporting requirements, activity data from the Manufacture of Solid Fuels and Other Energy Industries category were reallocated to two separate IPCC subcategories, both of which comprise the emissions associated with the combustion of fuels produced at the facilities (e.g. combustion of coal at a coal mine or natural gas at an oil and gas facility) as well as the combustion of purchased fuels. Combustion emissions that support coal production are allocated to 1.A.1.c.i – Manufacture of Solid Fuels, while combustion emissions that support crude oil and natural gas production and upgrading of oil sands bitumen are allocated to 1.A.1.c.ii – Oil and Gas Extraction.

The methodology for estimating emissions from these subcategories involves applying Equation A3.1–1 on a national basis and subtracting emissions associated with flaring from the total GHG emissions for Petroleum Refining and Oil and Gas Extraction. The fuel use data reported in the RESD include volumes of flared fuels; however, flaring emissions are calculated and reported separately in the Fugitive category. To avoid double counting, the model subtracts fuel use, energy content and emission data associated with flaring. See Annex A3.2.2.7 for more details.

Determining the activity data associated with the Petroleum Refining subcategory requires the reallocation of some of the data reported as Producer Consumption in the RESD. The Petroleum Refining subcategory includes all refined petroleum products reported as Producer Consumption, except in provinces where no refinery exists; these producer-consumed RPPs are assigned to Oil and Gas Extraction. Physical quantities of liquefied petroleum gases (LPGs) reported in the RESD as producer consumption are divided between propane and butane using energy data reported in the RESD.

Calculating the emissions associated with the fuels listed below involves summing the activity data reported under the RESD's Petroleum Refining and Producer Consumption lines and applying Equation A3.1–1 to:

- petroleum coke
- still gas
- kerosene
- light fuel oil
- heavy fuel oil
- butane
- propane

In addition, activity data in the form of fuel used by industry to generate electricity or steam are currently aggregated to two summary lines in the RESD (Line 11 – Electricity by Industry and Line 14 – Steam Generation). The aggregated data need to be reallocated to the appropriate industry where the fuel is used. Reallocation involves one of the two methods discussed in detail in section A3.1.4.1. Because of a lack of resolution in the RESD Producer Consumption line by specific industry, the Manufacture of Solid Fuels and Other Energy Industries subcategory does not include emissions associated with the transportation fuels listed below; these emissions are reported in the Petroleum Refining subcategory. In general, the combustion emissions calculations from the following transportation fuels, for the Petroleum Refining subcategory, use activity data reported in the RESD under Producer Consumption, together with Equation A3.1–1:

- aviation gasoline
- aviation turbo fuel
- diesel
- motor gasoline

The estimated N₂O emissions for petroleum coke and motor gasoline use IPCC default emission factors, which are based on the calorific value of the fuel. The RESD reports the gross calorific value for petroleum coke, and this can change annually. As a result, the petroleum coke emission factors for both crude bitumen upgrading and crude oil refining change on an annual basis. The conversion between the gross calorific value and the net calorific value, a necessary step in generating annual emission factors, uses data reported to, and published by, the Canadian Energy and Emissions Data Centre (CEEDC) (CEEDC, 2012).

To calculate GHG emissions from the Manufacture of Solid Fuels and Oil and Gas Extraction subcategories, activity data associated with the fuels listed below and reported under the Producer Consumption line and applicable portion of the Total Mining and Oil and Gas Extraction line of the RESD are used in Equation A3.1–1:

- natural gas
- coal
- diesel
- propane
- butane
- petroleum coke
- still gas
- heavy fuel oil

The Producer Consumption line of the RESD includes petroleum coke, still gas and diesel used by refineries and by the crude bitumen upgrading industry. Information on the proportion of fuel consumed by the crude bitumen upgrading industry is provided in Table 11, Estimated Additions to Still Gas, Diesel, Petroleum Coke and Crude Oil, of the RESD. This information is used to reallocate the relevant quantities of petroleum coke and still gas to the Oil and Gas Extraction subcategory (CRF category 1.A.1.c.ii). Diesel reported as producer consumption is used in oil sands mining trucks and is reallocated to Other Transportation (Off-Road) (see section A3.1.4.2.1).

The Total Mining and Oil and Gas Extraction line of the RESD includes fuel consumption that occurs at coal mines, non-energy mines (including metal mining, sand, gravel and other aggregate mining, potash mining, diamond mining, etc.) and at facilities involved in the production of crude oil and natural gas. The RESD does not contain a sufficient level of detail to separate the fuel consumed at coal mines, non-energy mines and oil and gas extraction operations to allocate into the following CRF categories; Manufacture of Solid Fuels (1.A.1.c.i), Mining (1.A.2.g.iii), and Oil and Gas Extraction (1.A.1.c.ii). Other data sources therefore are used to allocate the fuel consumption to the proper categories. Fuel consumption at coal mining operations is estimated based on data from the study of the Canadian coal mining industry (Cheminfo and Clearstone, 2014), while fuel consumption for the non-energy mining industry is based on data from the Canadian Energy and Emissions Data Centre (CEEDC, n.d.; NAICS 2122 and 2123). As the oil and gas industry in Canada is the largest of these three industries, the remainder of fuel consumed in the Total Mining and Oil and Gas Extraction line after subtracting coal mining and non-energy mining fuel consumption is allocated to Oil and Gas Extraction. For a more detailed explanation of the allocation procedure, please see Annex 10 – Reallocation of Emissions from IPCC Sector to Canadian Economic Sector.

As previously mentioned in section A3.1.4.1.1, national level coal emissions from combusted coal use aggregated provincial and territorial level estimates.

Table A3.1–3 Estimation Methodology for Petroleum Refining, Manufacture of Solid Fuels and Oil and Gas Extraction

CRF Source Category ^a	Fuel Type ^b	Data Source		
		Publication ^c	Table	Line
1.A.1.b Petroleum Refining	Solid Fuels	NA		
	Liquid Fuels	RES	3 – Refined Petroleum Products 11 – Estimated Additions to Still Gas, Diesel, Petroleum Coke and Crude Oil	Electricity by Industry ^d Steam Generation ^d NA
	Gaseous Fuels	RES	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	Electricity by Industry ^d Steam Generation ^d Refined Petroleum Products Manufacturing
	Biomass	NA		
1.A.1.c.i Manufacture of Solid Fuels	Solid Fuels	RES	1 – Primary and Secondary Energy Coal Details (unpublished)	Producer Consumption Total Mining and Oil and Gas Extraction ^e
	Liquid Fuels	RES	3 – Refined Petroleum Products	
	Gaseous Fuels	RES	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	NA		
1.A.1.c.ii Oil and Gas Extraction	Solid Fuels	NA		
	Liquid Fuels	RES	3 – Refined Petroleum Products 6 – Details of Natural Gas Liquids 11 – Estimated Additions to Still Gas, Diesel, Petroleum Coke and Crude Oil	Electricity by Industry ^d Producer Consumption Total Mining and Oil and Gas Extraction ^f NA
	Gaseous Fuels	RES	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	Electricity by Industry ^d Producer Consumption Total Mining and Oil and Gas Extraction ^f
	Biomass	NA		

Notes:

NA = Not applicable (national aggregation only)

a. The CRF categories listed are the lowest-level subcategories for which emissions are estimated.

b. As outlined in IPCC (2006) (Volume 2, Table 1.1).

c. Publication references are provided in Table A3.1–1.

d. A portion of this data source is allocated to this CRF source category prior to calculating emissions.

e. The portion of fuel consumed at coal mining operations is allocated to this CRF category.

f. The portion of fuel consumed at oil and gas extraction facilities is allocated to this CRF category.

Table A3.1–3 provides a summary of the methodology for this CRF category.

A3.1.4.1.3. Manufacturing Industries and Construction (CRF Category 1.A.2)

The Manufacturing Industries and Construction category includes a number of industrial categories. Activity data in the RESD are reported for the main economic and fuel-consuming industrial categories; however, this does not include fuel used to generate electricity or steam by industry. This energy is captured in the RESD in two separate summary lines (one for electricity and one for steam), which are not broken down by industrial categories. In addition, activity data, in the form of solid wood waste and spent pulping liquor, are currently aggregated to a summary table in the RESD (Table 10 – Consumption of Solid Wood Waste and Spent Pulping Liquor for Energy Production). The aggregated data need to be reallocated to the appropriate industry where the fuel is used. Section A3.1.4.1 describes this reallocation method in detail.

Emissions are calculated for the following categories:

- Mining
- Iron and Steel
- Non-ferrous Metals
- Chemicals
- Pulp, Paper and Print
- Non-metallic Minerals
- Construction
- Other Manufacturing (includes Food Processing, Beverages and Tobacco)

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GHG emissions associated with the Manufacturing Industries and Construction category are calculated by applying Equation A3.1–1 to activity data reported in the RESD and corresponding emission factors for each fuel type (as presented in A6.1). Section A3.1.4.1.1 describes the handling of coal emissions. The Industrial Processes and Product Use sector reports emissions from fuels used as feedstocks, while the Transport category reports emissions generated from the use of transportation fuels (e.g. diesel and gasoline).

The Industrial Processes and Product Use sector reports all emissions associated with the manufacture and use of metallurgical coke in the iron and steel industry for the reduction of iron ore in blast furnaces.

Industrial consumption of biomass and spent pulping liquor is reported in the RESD; however, some of the data are limited. The RESD data for Newfoundland and Nova Scotia are combined. Facility-level data are used to reallocate this consumption to Nova Scotia.

As previously described in section A3.1.4.1.2 the Total Mining and Oil and Gas Extraction line in the RESD includes fuel consumption that occurs at coal mines, non-energy mines (including metal mining, sand, gravel and other aggregate mining, potash mining, diamond mining, etc.) and at facilities involved in the production of crude oil and natural gas. The RESD does not contain a sufficient level of detail to separate the fuel consumed at coal mines, non-energy mines and oil and gas extraction operations for allocation to the Manufacture of Solid Fuels (1.A.1.c.i), Mining (1.A.2.g.iii), and Oil and Gas Extraction (1.A.1.c.ii) categories, respectively. Other data sources are therefore used to allocate the fuel consumption to the proper categories. Fuel consumption for the non-energy mining industry is based on data from CEECD (n.d.; NAICS 2122 and 2123). For a more detailed explanation of the allocation procedure, please see Annex 10 – Reallocation of Emissions from IPCC Sector to Canadian Economic Sector.

The Other Manufacturing category also includes GHG emissions associated with the combustion of waste for energy purposes. A portion of the waste is considered biogenic, so CO₂ emissions associated with combustion of this portion are reported but not included in the national total. The CO₂ emissions associated with the combustion of the non-biogenic portion, along with the total CH₄ and N₂O emissions, are included in the national total.

CO₂ emissions from the combustion of waste fuels in the cement industry are calculated using data provided by the Cement Association of Canada and reported by CEECD (2013) on an energy basis. Table A3.1–4 provides a summary of the methodology for the Non-Metallic Minerals category.

A3.1.4.1.4. Other Sectors (CRF Category 1.A.4)

The Other Sectors category consists of three subcategories: Commercial/Institutional, Residential, and Agriculture/Forestry/Fishing. GHG emissions associated with the Other Sectors category (with the exception of emissions from the combustion of residential firewood) are calculated by applying Equation A3.1–1 to activity data reported in the RESD and corresponding emission factors for specific fuels (refer to Annex 6.1).

The activity data used in the calculation of GHG emissions from the combustion of residential firewood are based on estimated fuel use, as determined from the *Residential Fuelwood Consumption in Canada* study (ECCC, 2020). Firewood consumption data were collected through a survey of residential wood use for the years 1997, 2003, 2007, 2015, 2017 and 2019 (Statistics Canada, 1997, 2003, 2007, 2015, 2017, 2019). Pellet and manufactured log consumption data were collected for the years 1996, 2006, 2012, 2017 and 2019 (Canadian Facts, 1997; TNS, 2006; TNS, 2012; Statistics Canada, 2017, 2019). These data were collected by province and grouped into eight major appliance-type categories:

- Fireplaces
- Fireplace Inserts
- Wood Stoves
- Wood Furnaces
- Pellet Stoves
- Hydronic Heater
- Water Heater
- Other Equipment

Some of these appliance types were further broken down into either advanced technology (catalytic or non-catalytic) or conventional technology (air-tight or not-air tight).

The 2017 and 2019 surveys also collected data on the type of wood used, by reconciliation unit, and the moisture content of the wood. Section A3.5.1 describes the boundaries of reconciliation units in detail. Since the firewood consumption data were collected on a volume basis, an average density value was determined by reconciliation unit, based on the proportion of the different types of wood used, the corresponding wood densities and the moisture content of the wood. The wood densities were taken from various Canadian wood density studies (Alemdag, 1984; Gonzalez, 1990; Jessome, 2000). The ratio of wood used, by reconciliation unit, and the moisture content of the wood compared to the total firewood consumption in the province was applied to all surveys. The pellet and manufactured log consumption data were collected on a mass basis.

Table A3.1–4 Estimation Methodology for Manufacturing Industries and Construction

CRF Source Category ^a	Fuel Type ^b	Publication ^c	Data Source	
			Table	Line
1.A.2.a. Iron and Steel	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Steam Generation ^d Iron and Steel Manufacturing
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RESD	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
1.A.2.b. Non-Ferrous Metals	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Steam Generation ^d Aluminium and Non-ferrous Metal Manufacturing
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RESD	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
1.A.2.c. Chemicals	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Steam Generation ^d Chemicals and Fertilizer Manufacturing
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RESD	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
1.A.2.d. Pulp, Paper and Print	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Steam Generation ^d Pulp and Paper Manufacturing
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RESD	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
1.A.2.e. Food Processing, Beverages and Tobacco	Emissions for this subcategory are included in 1.A.2.g.viii.1 Other Manufacturing			
1.A.2.f. Non-Metallic Minerals	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Steam Generation ^d Cement
			Waste fuel data from the Canadian Energy and Emissions Data Centre (CEEDC)	
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RESD	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
1.A.2.g.iii Mining	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Steam Generation ^d Total Mining and Oil and Gas Extraction ^f
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RESD	NA	
1.A.2.g.v Construction	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Construction
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Biomass	RESD	NA	
1.A.2.g.viii.1 Other Manufacturing	Solid Fuels	RESD	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Steam Generation ^d Other Manufacturing
	Liquid Fuels	RESD	3 – Refined Petroleum Products	
	Gaseous Fuels	RESD	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Other Fossil Fuels	NIR	Table A3.6–13 ^e	
	Biomass	RESD	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
		NIR	Table A3.6–13 ^e	

Notes:

NA = Not applicable (national aggregation only)

a. The CRF categories listed are the lowest-level subcategories for which emissions are estimated.

b. As outlined in IPCC (2006) (Volume 2, Table 1.1).

c. Publication references are provided in Table A3.1–1.

d. A portion of this data source is allocated to this CRF source category prior to calculating emissions.

e. The non-biogenic portion of MSW incineration is included under Other Fossil Fuels, the biogenic portion is under biomass.

f. The portion of fuel consumed at non-energy mining operations is allocated to this CRF category.

The mass of biomass consumed for the other years was interpolated and extrapolated using the number of heating degree days in each province in relation to the survey years. GHG emissions were calculated by multiplying the amount of biomass burned in each appliance by the emission factors.

CO_2 emissions associated with biomass combustion in the Residential category are reported but not included in the national total. CH_4 and N_2O emissions are, however, included.

The Commercial/Institutional category includes GHG emissions associated with the combustion of landfill gas. As landfill gas is considered a biofuel, CO_2 emissions associated with combustion are reported but not included in the national total. CH_4 and N_2O emissions are, however, included.

The Commercial/Institutional category also includes GHG emissions associated with the combustion of waste for energy purposes. A portion of the waste is biogenic, and CO_2 emissions associated with combustion of this portion are reported but not included in the national total. The CO_2 emissions associated with the combustion of the non-biogenic portion, along with the total CH_4 and N_2O emissions, are included.

In addition, activity data in the form of fuel used by industry (including the Commercial/Institutional category) to generate electricity are currently aggregated to a summary line in the RESD (Line 11 – Electricity by Industry). Activity data in the form of solid wood waste and spent pulping liquor are currently aggregated to a summary table in the RESD (Table 10 – Consumption of Solid Wood Waste and Spent Pulping Liquor for Energy Production). The aggregated fuel use data need to be reallocated to the appropriate subcategory. Section A3.1.4.1 discusses the disaggregation method used.

The Agriculture/Forestry/Fishing category (CRF category 1.A.4.c) includes emissions from stationary fuel combustion only from the agricultural and forestry industries. Emissions are from on-site machinery operation and space heating and are estimated using fuel use data for agriculture and forestry as reported in the RESD. Fishery emissions are reported under either the Transport or Other Manufacturing (i.e. food processing) category. Mobile emissions associated with this category are not disaggregated and are all included as off-road or marine emissions reported under the Transport category.

Table A3.1–5 provides a summary of the methodology for this CRF category.

Table A3.1–5 Estimation Methodology for the Other Sectors Category

CRF Source Category ^a	Fuel Type ^b	Data Source		
		Publication ^c	Table	Line
1.A.4.a.i Commercial/Institutional – Stationary Combustion	Solid Fuels	RES	1 – Primary and Secondary Energy Coal Details (unpublished)	Electricity by Industry ^d Commercial and Other Institutional Public Administration
	Liquid Fuels	RES	3 – Refined Petroleum Products	
	Gaseous Fuels	RES	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	
	Other Fossil Fuels	NIR	Table A3.6-13 ^e	
	Biomass	RES	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	
		NIR	Table A3.6-13 ^e	
		NIR	Table A3.6-6	
1.A.4.b.i Residential – Stationary Combustion	Solid Fuels	RES	1 – Primary and Secondary Energy Coal Details (unpublished)	Residential
	Liquid Fuels	RES	3 – Refined Petroleum Products	Residential
	Gaseous Fuels	RES	1 – Primary and Secondary Energy 6 – Details of Natural Gas Liquids	Residential
	Biomass	Estimated using Environment Canada residential fuelwood consumption model.		
	1.A.4.c.i Agriculture/Forestry/Fishing – Stationary Combustion	Solid Fuels	RES	Electricity by Industry ^d Steam Generation ^d Forestry and Logging and Support Activities for Forestry Agriculture
		Liquid Fuels	RES	
		Gaseous Fuels	RES	
		Biomass	10 – Solid Wood Waste and Spent Pulping Liquor, Total Consumption ^d	

Notes:

- a. The CRF categories listed are the lowest-level subcategories for which emissions are estimated.
- b. As outlined in IPCC (2006) (Volume 2, Table 1.1).
- c. Publication references are provided in Table A3.1–1.
- d. A portion of this data source is allocated to this CRF source category prior to calculating emissions.
- e. The non-biogenic portion of MSW incineration is included under Other Fossil Fuels and the biogenic portion under Biomass.

A3.1.4.2. Transport (CRF Category 1.A.3)

GHG emissions from the Transport category are divided into six subcategories:

- Domestic Aviation
- Road Transportation
- Railways
- Domestic Navigation
- Other Transportation (Pipeline Transport)
- Other Transportation (Off-Road)

Emission estimates are developed at the provincial and territorial level and aggregated to the national level. Fuel combustion emissions associated with the Transport category are calculated using various adaptations of Equation A3.1–1.

CO_2 emissions are predominantly dependent on the type and characteristics of fuel being combusted, whereas N_2O and CH_4 emissions are dependent on both the fuel combusted and emission control technologies present. Annex 6 provides a complete listing of transportation-related emission factors and their specific references.

For the Road Transportation and Other Transportation (Off-Road) categories, Canada uses the Motor Vehicle Emissions Simulator (MOVES) model, MOVES2014 version, developed by the United States Environmental Protection Agency (U.S. EPA), and a modified version of the U.S. EPA's NONROAD model (NONROAD2012c). The primary reasons for these updates are to remain current with regulatory changes in the Canadian vehicle fleet, which are harmonized with those of the United States, to align GHG estimates with those published in *Canada's Air Pollutant Emissions Inventory Report 1990–2020* and *Canada's Black Carbon Inventory Report 2013–2020* and to create a bottom-up inventory for off-road emissions by making use of equipment and operational data. Use of the NONROAD model also has the added benefit of allocation to additional economic subsectors on an equipment basis. Therefore, under the CRF classification system, some emissions that were previously reported in the 1.A.3 categories are allocated to the 1.A.2 and 1.A.4 categories. The Aviation Greenhouse Gas Emission Model (AGEM) is used to calculate aviation emissions. The Marine Emissions Inventory Tool (MEIT) is used to calculate navigation emissions. Railway emissions are derived from fuel reported in the RESD. Combustion emissions associated with pipeline transport are estimated separately.

A3.1.4.2.1. Road Transportation (CRF Category 1.A.3.b.i-v) and Other Transportation (Off-Road) (CRF Categories 1.A.2.g.vii, 1.A.3.e.ii, 1.A.4.a.ii, 1.A.4.b.ii and 1.A.4.c.ii)

The methodology used to estimate Road Transportation and Other Transportation (Off-Road) GHG emissions follows a detailed IPCC Tier 3 approach. Since these two categories are collectively normalized to fuel available as reported in the RESD, a combined methodology for the two categories is outlined below.

Step 1: On-Road Activity Data – Vehicle Populations, Technology Penetration, Kilometre Accumulation Rates, Fuel Consumption Rates and Biofuels

Vehicle Populations

Vehicles are separated into different classes depending on their fuel type, body configuration (car versus truck) and gross vehicle weight rating (GVWR). GVWR is the maximum allowable weight of a fully loaded road vehicle, including the weight of the vehicle, fuel, passengers, cargo and other miscellaneous items, including optional accessories.

Two distinct data sets are used to develop a complete vehicle population profile. Light-duty vehicle and truck populations for 1990–2002 and 2005–2015 were obtained from the Canadian Vehicles in Operation Census, which is maintained by DesRosiers Automotive Consultants Inc. Light-duty vehicle and truck populations for 2003–2004 were derived from Statistics Canada's Canadian Vehicle Survey. Heavy-duty vehicle populations were obtained from R.L. Polk & Co. for 1994–2002 and 2005–2015. Heavy-duty vehicle populations for 2003–2004 were derived from Statistics Canada's Canadian Vehicle Survey, while populations for 1990–1993 were estimated based on historical population trends. The 2016–2020 populations were estimated based on scrappage and growth rates.¹ Light-duty vehicles (cars) and light-duty trucks (pickups, minivans, SUVs, etc.) are those with a GVWR of less than or equal to 3900 kg, whereas heavy-duty classes have a GVWR above 3900 kg.²

¹ Scrappage rates for all vehicle classes (including motorcycles) were developed based on historical population trends. The growth rates for light-duty vehicles and motorcycles are from the U.S. EPA Motor Vehicle Emission Simulator (U.S. EPA, 2021). For all other classes, Power Systems Research Inc. provided growth rates.

² The 2005–2015 light- and heavy-duty populations received from DesRosiers and Polk were in a new format when compared with previously received data sets and were derived using updated vehicle identification algorithms. As a result, when the 1990–2004 data set was merged with the 2005–2015 data set, there were step changes in some classes between 2004 and 2005. The classes affected were light-duty trucks (GVWR less than or equal to 3900 kg) and heavy-duty vehicle 2b and 3 classes (GVWR between 3901 kg and 6351 kg). Since the newer data set with updated algorithms is believed to be more representative, the class ratios between light-duty trucks and heavy-duty vehicle 2b and 3 classes from the newer data were applied to the older data set while maintaining the overall population of the older data set.

Motorcycle populations for 1990–2013 were based on road motor vehicle annual registrations from Statistics Canada (CANSIM, Table 405-0001 and Table 405-0004). The annual motorcycle counts were then stratified into model year bins with the aid of published age distributions found in the Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. EPA, 2015). The 2014–2020 population was estimated based on a scrappage and growth rate.

Technology Penetration

To account for the effects of emission control technologies on emission rates of CH₄ and N₂O, estimates of the number of vehicles on the road equipped with catalytic converters and other control technologies were developed. The vast majority of on-road vehicles in use in 2020 are subject to Tier 1 and Tier 2 regulatory tiers, approximately representing model years 1996 and onwards. However, since the National Inventory estimates a time series starting at 1990, as well as considering a small number of pre-1996 model year vehicle still in active fleet, additional technology emission rates for CH₄ and N₂O emission factors are also used. These include emission controls ranging from completely uncontrolled vehicles to those using Tier 1 regulatory standards. Similarly, heavy-duty gasoline vehicles, heavy-duty diesel vehicles and motorcycles have advanced emissions controls starting with the 1996 model year. Emission factors for uncontrolled and/or moderate controls are used for 1995 and older model years. CH₄ and N₂O emission factors for the full range of emission controls are listed in Annex 6.

Fuel Consumption Rates (FCR)

With the adoption of MOVES2014, fuel consumption rates are now embedded within the model in the form of energy rates in kilojoules per second (kJ/s). The rates vary, taking into account a range of default parameters or user inputs, such as vehicle type, model year, speed, road type and operating mode. As the Canadian and U.S. vehicle markets are made virtually identical through regulation, it is believed that the MOVES energy rates are representative of fuel consumption for Canadian vehicles. MOVES also factors in more current fuel efficiency regulations, such as the *On-Road Vehicle and Engine Emission Regulations* for light-duty vehicles and the *Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations* for heavy-duty vehicles. Further documentation on MOVES energy rates for both light- and heavy-duty vehicles can be found on the U.S. EPA website at <https://www.epa.gov/moves/moves-technical-reports>.

For this submission, Canada only uses MOVES' energy allocation capability. MOVES output is on an energy basis and Canada's current emission factors are developed on a fuel-volume basis. The energy output from MOVES is therefore converted to fuel volumes using energy conversion factors, as reported in *Updated CO₂ Emission Factors for Gasoline and Diesel Fuel* (ECCC 2017b), taking into consideration the use of biofuels (see below). MOVES reports energy output on a lower heating value basis. Canada plans to review the GHG emission factors within MOVES for their potential use in a future submission.

Kilometre Accumulation Rates

Kilometre accumulation rates (KARs) are a measure of the average annual kilometres travelled by a single vehicle of a given age in a specific vehicle class. Light-duty car and truck KARs are estimated from the results reported in a study that examined observed differences in a vehicle odometer reading recorded between successive inspection and maintenance tests from Ontario and British Columbia (Stewart Brown Associates, 2013). Given the absence of inspection and maintenance programs in other jurisdictions, the Ontario KAR estimates are adopted in all other provinces and territories excluding British Columbia, where the B.C. KAR estimates are directly applied.

Biofuels

MOVES requires biofuel content on a relative content basis (i.e., percent) as an input, as well as a range of other fuel characteristics, such as vapour pressure, sulphur content, and benzene content. These parameters are derived by ECCC using information collected under the *Renewable Fuels Regulations*, *Sulphur in Liquid Fuels* reports and related sources. However, volumes of biofuels are recalculated as outputs such that emissions can be estimated by selecting appropriate emission factors in Annex 6 and applying Equation A3.1–1.

Step 2: On-Road Fuel Calculation

Using the inputs from Step 1, on-road fuel consumption is estimated by converting MOVES2014 energy outputs into litres of fuel volume. This calculation represents the initial “bottom-up” fuel calculation for consideration in the fuel normalization process described below. On-road vehicles are grouped into eight major vehicle classes:

- Light-duty gasoline vehicles
- Light-duty gasoline trucks
- Heavy-duty gasoline vehicles
- Motorcycles
- Light-duty diesel vehicles
- Light-duty diesel trucks
- Heavy-duty diesel trucks
- Propane and natural gas vehicles

Step 3: Other Transportation (Off-Road) (CRF Category 1.A.3.e.ii)

GHG emissions for off-road transportation are calculated using NONROAD2012c, a Canadianized update to NONROAD2008 developed by the U.S. EPA. Key inputs to the model are equipment population, average rated power, load factor and activity (in hours/year). Further, the Canadian modifications to NONROAD include a user-defined age distribution of equipment that is not part of the U.S. model, as well as a unique coding for oil sands equipment and additional renewable fuels capabilities. NONROAD outputs are expressed on a fuel volume basis, to which Equation A3.1–1 is applied using the emission factors in Annex 6.

Activity data used in the model are largely derived from Power Systems Research (PSR) data. PSR is an independent supplier of data which maintains PartsLink, a comprehensive database that includes off-road equipment used in Canada. A significant study conducted by PSR in 2011 forms the basis of activity input, which includes parameters such as engine populations, age distribution, engine size, load factor and hours of use for the years 1990 to 2020. Construction equipment populations used in oil sands mining operations were identified with a mining equipment database provided by The Parker Bay Company (ECCC, 2018a). Where possible, the hours-of-use parameter provided by PSR was replaced using Canada-specific information collected from resale markets. As an example, activity data from nearly 2000 used snowmobile advertisements were used to derive hours-of-use data, by engine stroke (ECCC, 2018b). NONROAD default parameters used include deterioration and other factors. Updates to the 2011 data set were performed in 2012 and 2013. Unlike MOVES, which outputs on an energy basis, NONROAD calculates fuel use on a volume basis, which is later scaled upwards or downwards in the fuel normalization step (Step 4) once biofuels are taken into account.

A great advantage of NONROAD is its capability to allocate emissions to distinct sectors on an equipment basis. Primary sectors from NONROAD include agriculture, airport (equipment), commercial, construction and mining, industrial, residential, forestry, railway (equipment) and recreational equipment. Where applicable, emissions from these sectors are reported under the appropriate CRF sector.

Step 4: Normalization

In an effort to mitigate some of the uncertainties associated with separate bottom-up calculations for on- and off-road estimates, the fuel consumption estimates from these two subsectors are combined and balanced against top-down fuel availability information. The source of top-down fuel availability data to be considered against the bottom-up fuel consumption estimate is the RESD (Statistics Canada, 1990–).

Statistics Canada has stated that the volumes of gasoline reported in the RESD include ethanol. Therefore, the estimated volume of ethanol fuel is removed from the volume of gasoline reported. As a result, when comparing total volumes of gasoline in the RESD with that of the CRF, one should be cognizant that the CRF gasoline volume must be added to the CRF ethanol volume in order to equate to the RESD gasoline volume. For diesel fuel, the opposite is true: given that the RESD does not report biodiesel, diesel fuel volumes in the CRF will equate to the diesel fuel volumes in the RESD.

In Step 4, bottom-up estimates of fuel consumption from on- and off-road sources are pooled together on a fuel basis at the provincial and territorial level, and the total volume of fuel is scaled to match the fuel available as reported in the RESD. At a provincial level, top-down and bottom-up gasoline consumption estimates differ slightly; however, at a national level, the degree of correlation between the two estimates is higher. Please refer to Table A3.1–6 and Table A3.1–7 for the normalization factors calculated on a national basis for gasoline and diesel fuel, respectively.

Step 5: Emission Calculation

Once a final allocation of fuel is complete for all vehicle and equipment types, emissions are calculated using Equation A3.1–1 with the emission factors in Annex 6.

Table A3.1–6 Gasoline Normalization Values, Selected Years

Category	Statistic	1990	2005	2014	2015	2016	2017	2018	2019	2020
Raw	Bottom-Up On-Road Fuel Consumption Estimate (ML)	37 110	40 653	49 418	50 529	50 340	50 203	51 356	52 251	42 681
	Bottom-Up Off-Road Fuel Consumption Estimate (ML)	7 462	3 189	3 463	3 531	3 335	3 458	3 581	3 518	3 390
	Total Bottom-Up Fuel Consumption Estimate (ML)	44 572	43 842	52 881	54 060	53 675	53 661	54 937	55 770	46 071
	Bottom-Up On-Road Portion (%)	83	93	93	93	94	94	93	94	93
	Bottom-Up Off-Road Portion (%)	17	7	7	7	6	6	7	6	7
Target	Total Top-Down Fuel Available (ML)	33 943	40 868	43 437	44 423	46 046	46 393	47 033	47 632	40 427
	National Scaling Factor (%)	76	93	82	82	86	86	86	85	88
Scaled	Final On-Road Fuel Estimate (ML)	28 298	37 886	40 567	41 493	43 160	43 388	43 957	44 620	37 447
	Final Off-Road Fuel Estimate (ML)	5 645	2 982	2 870	2 930	2 886	3 005	3 076	3 012	2 980
	Sum of Final On- and Off-Road Fuel (ML)	33 943	40 868	43 437	44 423	46 046	46 393	47 033	47 632	40 427

A3.1.4.2.2. Domestic Aviation (CRF Category 1.A.3.a)

The methodology used to estimate GHG emissions from the Domestic Aviation category employs a modified IPCC Tier 3 approach. The Aviation model has been named AGEM as an acronym for Aviation Greenhouse Gas Emission Model.

This category includes all emissions from domestic air transport (commercial, private, agricultural, etc.). In accordance with the 2006 IPCC Guidelines, and because of the Tier 3 approach, military air transportation emissions are reported in the Other – Mobile category (CRFcategory 1.A.5.b). Excluded are emissions from fuel used at airports for ground transport, which are reported under Other Transportation (Off-Road), and emissions from fuel used in stationary combustion applications at airports. Emissions from international flights are designated as “bunker” emissions and are not included in national totals, but are estimated and reported separately under International Bunkers.

Careful consideration should be paid when comparing emission estimates in this category against those reported to other institutions, such as the International Energy Agency (IEA). The IEA estimates are, in particular, quite different from those reported in the CRF when comparing domestic and international (bunker) emissions from aviation turbo fuel. The Tier 3 method employed by AGEM in the NIR allows detailed flight-by-flight distinction between domestic and international movements based on a flight's origin and destination. The fuel consumption values (disaggregated into domestic and international sectors) reported to the IEA by Canada assume that all fuel sold to Canadian carriers is domestic and that all fuel sold to foreign carriers is international, which greatly underestimates the amount of emissions identified as aviation bunkers, given that many movements by Canadian carriers are international in nature. Because the reporting requirements for these two separate reports (UNFCCC, IEA) do not align, the reported values will not align either.

Step 1: Activity Data: Aircraft Movements, Flight Path Length, Airport Coordinates, Aircraft Fuel Use Characteristics, Representative Aircraft Mapping, Aircraft Emission Performance

Aircraft Movements

The aircraft movement data (AMS, 2020) used in AGEM are flight-by-flight tower data collected by NAV Canada (Canada's civil air navigation services provider) starting in November 1996 and by Transport Canada before November 1996. Both data streams are processed by Statistics Canada and redistributed to NAV Canada and Transport Canada. ECCC receives the information directly from Statistics Canada, including small airport movements that Statistics Canada collects directly and appends to the tower data from NAV Canada.

The data identify, among other things, the origin, destination and aircraft type for any given movement occurring in Canada. Statistics Canada's processing of the data includes adding information based on other raw data fields provided to it as well as validation of airports, aircraft types and various data fields that are not crucial to modelling fuel use.

Military emissions are estimated on the basis of movement data, as they are labelled as military by Statistics Canada.

Flight Path Length

The flight path length is the true distance travelled between two airports. The movement data used for modelling are not radar data and thus do not track the exact path travelled by each individual movement. AGEM estimates the flight path length based on additional information obtained from the Federal Aviation Administration (FAA). The FAA operates an aviation model called the Aviation Environmental Design Tool (AEDT) (formerly System for Assessing Aviation's Global Emissions [SAGE]) that is based on true radar data. The FAA provided Environment Canada with an extract from its model for calendar year 2005 involving Canadian airports and included the statistical measures (maximum, minimum, average, standard deviation) for the radar distance travelled between any Canadian origin and final destination for a given aircraft type (Fleming, 2008a). The average distance from these combinations was then used as the distance flown when the same

Table A3.1-7 Diesel Fuel Normalization Values, Selected Years

Category	Statistic	1990	2005	2014	2015	2016	2017	2018	2019	2020
Raw	Bottom-Up On-Road Fuel Consumption Estimate (ML)	5 323	14 638	19 489	19 344	20 196	21 105	21 899	22 202	19 857
	Bottom-Up Off-Road Fuel Consumption Estimate (ML)	9 402	10 322	9 254	9 851	9 892	10 594	11 281	11 367	11 368
	Total Bottom-Up Fuel Consumption Estimate (ML)	14 726	24 960	28 743	29 195	30 089	31 699	33 180	33 569	31 225
	Bottom-Up On-Road Portion (%)	36	59	68	66	67	67	66	66	64
	Bottom-Up Off-Road Portion (%)	64	41	32	34	33	33	34	34	36
Target	Total Top-Down Fuel Available (ML)	13 188	22 785	27 483	27 409	26 143	27 964	29 498	29 309	27 423
	National Scaling Factor (%)	90	91	96	94	87	88	89	87	88
Scaled	Final On-Road Fuel Estimate (ML)	5 266	13 886	18 777	18 354	17 771	18 790	19 662	19 578	17 521
	Final Off-Road Fuel Estimate (ML)	7 922	8 898	8 706	9 056	8 372	9 174	9 835	9 731	9 902
	Sum of Final On- and Off-Road Fuel (ML)	13 188	22 785	27 483	27 409	26 143	27 964	29 498	29 309	27 423

combination appeared in AGEM's movement data (regardless of the calendar year of the movement). There are cases, however, when a combination in AGEM exists without a corresponding average distance. In these cases, another method needed to be developed.

An adjusted great circle distance (GCD³) is used when the average radar distance is unknown. A factor applied to the GCD was developed by comparing GCD to radar distance for a given origin/destination/aircraft type. Graphing the known radar lengths against their corresponding GCDs leads to an equation that can be used for adjusting all raw GCD distances. Therefore, all GCDs are adjusted by a factor to approximate the flight path length, with the factors decreasing in magnitude as the GCD increases.

Airport Coordinates

All possible airport entries within the AGEM movement data were extracted and defined. Information on the airports, such as latitude, longitude, name, and elevation, were compiled from various sources, including the 2009 and 2019 Canada Flight Supplement (NAV Canada, 2009, 2019a), 2018 and 2019 Canada Water Aerodrome Supplement (NAV Canada, 2018b, 2019b), Airport International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO) codes (NAV Canada, 2018a), the FAA (FAA, 2020), Airline and Location Code Search database (IATA, 2020), SAGE (Fleming 2008b), the Modeling and Database Task Force (MODTF) (Fleming, 2008c) and World Airport Codes (2020). The main data required to calculate a GCD for use in determining the flight path length are the geographical coordinates.

Aircraft Fuel Use Characteristics

Once the flight path length is determined, the fuel consumed by the aircraft for that movement can be calculated using the fuel characteristics of that aircraft. The fuel characteristics of various representative aircraft are drawn from the Base of Aircraft Data (BADA) (BADA, 2019), the ICAO via their engine emissions databank (ICAO 2019), the Swedish Defence Research Agency (FOI) via their turbo prop engine emissions databank (Hagstrom, 2010), and the Federal Office of Civil Aviation (FOCA) in Switzerland (FOCA, 2007).

Information from ICAO, FOI and FOCA is used to estimate fuel use for the taxi-out, taxi-in and takeoff phases of each flight. Information from BADA is used to estimate fuel use for the climb-out, climb, cruise, descent and landing phases of each flight.

Representative Aircraft Mapping

All possible aircraft type entries within the AGEM movement data were extracted and defined. Once defined, each aircraft was mapped to a representative aircraft with known fuel use characteristics so that fuel consumption could be calculated for all aircraft in AGEM. The mapping was done using published mapping guides whenever possible (BADA, 2019; FAA, 2018; IPCC, 2006; ICAO, 2016, 2020) and by matching aircraft characteristics (MTOW⁴, number of engines, engine type, etc.) when there was no published mapping for a given aircraft.

Aircraft Emission Performance

In an attempt to better estimate CH₄ emissions from aviation turbo fuel, aircraft-specific emission factors are used within AGEM, when applicable, for the LTO cycle. When there is no aircraft-specific CH₄ emission factor, the 2006 IPCC default factor is used. The factors are taken from Table 3.6.9 in the 2006 IPCC Guidelines and converted into grams per litre of fuel consumed. For the cruise portion, CH₄ emissions are assumed to be zero (Wiesen et al., 1994). For ease of use by the general public, the published CH₄ emission factor will be a fleet average across the entire time series and will be based on total fuel consumed (LTO and cruise).

Table 3.6.9 in the 2006 IPCC Guidelines also has N₂O aircraft-specific aviation turbo fuel emission factors on a total LTO cycle basis; however, they are calculated using a Tier 1 fuel-based emission factor. Therefore, the Tier 1 factor is used directly since the amount of fuel consumed during the LTO cycle is calculated by AGEM.

Country-specific emission factors on a g/L basis are used for CO₂ emissions from aviation turbo fuel aircraft and for CO₂, CH₄ and N₂O emissions from aviation gasoline aircraft.

³ Great circle distance is the shortest distance between two points on a sphere; with respect to aviation, it is the shortest possible flight path length between the origin and destination of a flight movement.

⁴ Maximum takeoff weight.

Step 2: Aircraft Fuel Calculation

Fuel consumed by each individual movement is estimated using the following equation.

Equation A3.1–2

$$FC_{FlightTotal} = FC_{Taxi-out} + FC_{Takeoff} + FC_{Climb-out} + FC_{Climb} + FC_{Cruise} + FC_{Descent} + FC_{Landing} + FC_{Taxi-in}$$

$FC_{FlightTotal}$	=	total fuel consumed on a per-flight basis
$FC_{Taxi-out}$	=	fuel consumption during the taxi-out phase
$FC_{Takeoff}$	=	fuel consumption during the takeoff phase
$FC_{Climb\ out}$	=	fuel consumption during the climb-out phase
FC_{Climb}	=	fuel consumption during the climb phase
FC_{Cruise}	=	fuel consumption during the cruise phase
$FC_{Descent}$	=	fuel consumption during the descent phase
$FC_{Landing}$	=	fuel consumption during the landing phase
$FC_{Taxi-in}$	=	fuel consumption during the taxi-in phase

The landing and takeoff (LTO) phase of flight (3000 ft and below) consists of takeoff (accelerating down the runway until liftoff), climb out (from liftoff to 3000 ft), landing (3000 ft to touchdown) and taxi in/out (manoeuvring from the airport runway to/from the gate). The various LTO phases of flight are quantified by using either standard time-in-modes for that phase multiplied by the fuel consumption rate for that phase (drawn from ICAO, FOI or FOCA) or BADA fuel use characteristics for the aircraft as applicable (only available for the climb-out and approach phases).

The cruise phase of flight (above 3000 ft) is calculated using the BADA fuel use characteristics of the aircraft and the flight path length of the movement. The cruise phase is broken up into three parts, consisting of climb (3000 ft to cruise altitude), steady-state cruise (constant cruise altitude reached after completion of climb) and descent (from cruise altitude to 3000 ft). The distance it takes to reach and descend from the steady-state cruise altitude (including the LTO portions of climb out and approach) is subtracted from the flight path length when determining the distance travelled at the steady-state cruise altitude.

The LTO and cruise phases of flight for any given movement are estimated by first using the representative aircraft mapping information, which relates the aircraft identified in the movement data to a representative aircraft with known performance characteristics. For the fuel rates of the representative aircraft that are distance-based, the flight path length for the movement is drawn from either the list of radar movement data provided by the FAA or calculated by quantifying the GCD and multiplying by an adjustment factor, as explained above. The fuel rates that are time-based in the LTO cycle already have the time-in-mode defined. With the known fuel characteristics of the aircraft, the time-in-mode and flight path length, the LTO and cruise fuel estimates can be computed.

Step 3: Normalization

All aviation turbo fuel and aviation gasoline consumed in Canada is reported in the RESD (Statistics Canada, 1990–). The fuel consumed, as estimated by the bottom-up approach of AGEM, is adjusted to match that of the RESD at a national level. The adjustment to LTO and cruise fuel estimates takes place at the individual movement level, across all movements.

Step 4: Emission Calculation

Emission estimates are generated at the individual movement level based on the normalized total fuel consumed and the appropriate emission factor, as outlined in Equation A3.1–1. The individual emission estimates are then summed to generate the national emission estimate.

A3.1.4.2.3. Domestic Navigation (CRF Category 1.A.3.d)

The methodology used to estimate GHG emissions from the Domestic Navigation category is considered an IPCC Tier 2 method for CO₂ emissions and an IPCC Tier 1 for CH₄, and N₂O emissions.

This category includes emissions from vessels navigating between Canadian ports. In accordance with the 2006 IPCC Guidelines, military marine transportation emissions are reported in the Other Mobile category (CRF category 1.A.5.b). Likewise, emissions from fishing vessels are reported in the Fishing category (CRF category 1.A.4.c.iii). Excluded are emissions from smaller recreational vessels (reported under Other Transportation (Off-Road)). Emissions from international voyages are designated as “bunker” emissions and are not included in national totals but are estimated and reported separately under International Bunkers as a Memo Item.

Marine emissions are developed using the MEIT, a model developed using vessel tracking information. Unlike the RESD, where fuel values are based on fuel sales data and organized by flag of vessel, MEIT is based on vessel movements and domestic or international emissions are assigned according to port origin destination information. Therefore, and similar to the Aviation subcategory, careful consideration should be paid when comparing fuel consumption (in terms of energy) in this subcategory against the national energy balance reported in the RESD and IEA data. Due to design and operating procedures of marine vessels, it is not uncommon for vessel to store significant amounts of fuel onboard. This means that it is possible for vessels to navigate in Canadian waters without purchasing fuel from a Canadian supplier. Since the RESD is based on fuel transactions in Canada, it is possible to have more fuel consumed in the marine sector than what is reported in the national energy balance. When using the reference approach, excess fuel is accounted for as a “temporary import.”

Step 1: Activity Data: Marine Emission Inventory Tool

The Marine Emission Inventory Tool uses vessel traffic data and vessel characteristics to estimate the quantity of fuel required for each vessel manoeuvre within Canadian waters. Vessel traffic data are used for the 2010, 2015, 2016, 2017 and 2018 calendar years. However, MEIT developed backcasts/forecasts for 1990 to 2050 in 5-year increments. Fuel quantities between those years were linearly interpolated. Since the 2015, 2016, 2017 and 2018 calendar years are the only years for which estimates are available at a detailed level, the proportions of fuel use for those years are applied to the other calendar years to further break down the fuel quantity.

For the 2010, 2015, 2016, 2017 and 2018 calendar years, the MEIT data are based on vessel traffic data from the Canadian Coast Guard Information System on Marine Navigation (INNAV) and Automatic Identification System (AIS) and the Department of Fisheries and Oceans' fishing license data. The vessel movements are grouped into 1-km segments, which provide the distance and time between each point. To estimate the fuel use, the vessel characteristics/classifications are taken into consideration. Three sources of fuel consumption are considered: main engines, auxiliary engines and boilers. MEIT uses general assumptions for the auxiliary engines and boilers, however, more parameters are used to determine the fuel consumed by the main engine. The load factor has a significant influence on the fuel estimate from the main engine and is therefore calculated for each data point based on the propeller law.

From 1990 to 2010 the data was backcasted using multiple factors including Transport Canada commodity data for 1990 to 2005, port dry bulk and containerized (TEU) data, Northwest and Canada Cruise Association (NWCCA) passenger data, and Statistics Canada population data.

From 2018 to 2050 the data was forecasted by scaling the ship movements per vessel class on the basis of estimated sector growth/contraction, and adjusting the emission factors on the basis of regulations and policies in place for that future year.

Step 2: Fuel allocation and time series consistency

The amount of fuel from the RESD is compared against the values estimated by the MEIT in order to determine how much of the fuel burned is likely to have been obtained from Canadian fuel suppliers. The comparison is performed systematically at a regional and category level.

In the event that the RESD values are greater than the fuel consumption values estimated by MEIT (Scenario 1), it is assumed that fuel values from MEIT for military, fishing, domestic and international navigation are all purchased from Canadian suppliers. Any fuel difference between the RESD and MEIT is attributed to the International Navigation (Bunkers) category. It is assumed in this scenario that the MEIT model underestimated the amount of fuel used for international navigation, which is likely due to the MEIT only covering movement within Canadian waters.

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In the event that the RESD values are less than the fuel consumption values estimated by MEIT (Scenario 2), the following procedure is followed:

Case 1 – Military. If the amount of fuel available in the RESD is greater than the amount of fuel estimated by MEIT to be used by military vessels, then it is assumed that all fuel used for military operations was obtained from Canadian suppliers. If the amount of fuel available in the RESD is less than the amount from MEIT, the portion of fuel equal to that of the RESD is assumed to be purchased from Canadian fuel suppliers, while the remainder of fuel used in that region is assumed to be purchased from a foreign fuel supplier.

Case 2 – Fishing. If the amount of fuel available in the RESD (minus that used for military operations) is greater than the amount of fuel estimated by MEIT to be used by fishing vessels, then it is assumed that all fuel used for commercial fishing was obtained from Canadian suppliers. If the amount of fuel available in the RESD is less than the amount from MEIT, the portion of fuel equal to that of the RESD is assumed to be purchased from Canadian fuel suppliers, while the rest of fuel used in that region is assumed to be purchased from a foreign fuel supplier.

Case 3 – Domestic Navigation. If the amount of fuel available in the RESD (minus that used for military and fishing operations) is greater than the amount of fuel estimated by MEIT used by vessels involved in domestic voyages, then it is assumed that all fuel used for domestic navigation was obtained from Canadian suppliers. If the amount of fuel available in the RESD is less than the amount from MEIT, the portion of fuel equal to that of the RESD is assumed to be purchased from Canadian fuel suppliers, while the rest of fuel used in that region is assumed to be purchased from a foreign fuel supplier.

Case 4 – International Navigation (Bunkers). The portion of fuel equal to the amount of fuel available in the RESD (minus that used for military, fishing and domestic navigation) is assumed to be purchased from a Canadian supplier to be used for international navigation (bunkers). Then the difference between the MEIT fuel and the RESD fuel is assumed to be purchased from foreign fuel suppliers.

Step 3: Emission Calculation

Emissions are calculated by multiplying the fuel quantity by the fuel-specific emission factors (see Annex 6).

A3.1.4.2.4. Railways (CRF Category 1.A.3.c)

The methodology is considered to be an IPCC Tier 2 method for CO₂ emissions and an IPCC Tier 1 for CH₄, and N₂O emissions. The national railway fuel consumption reported in the RESD (Statistics Canada, 1990–) is multiplied by fuel-specific emission factors (see Annex 6).

In Canada, locomotives are powered primarily by diesel fuel. A review of emissions attributable to steam train operations in Canada has determined that emissions associated with steam trains are insignificant. Electrically driven locomotives are accounted for under electricity production.

A3.1.4.2.5. Biomass (CRF Category 1.D.3)

The methodology used to estimate emissions from the consumption of biogenic transport fuels (ethanol and biodiesel) follows a modified IPCC Tier 1 method for gasoline and diesel fuel on-road transportation and an IPCC Tier 1 method for off-road transportation, railways and domestic marine. The volume of biofuels consumed for transportation is proportionally reallocated back into the respective diesel fuel and gasoline emission technology classes based on those classes' initial consumption volumes.

The volumes of biofuels used for on- and off-road transportation are described in section A3.1.4.2.1. The volumes of biofuels used for the rail and marine categories are based on information collected from Canada's *Renewable Fuels Regulations*. Currently, it is assumed that no biofuels are used in the aviation sector.

In lieu of specific CH₄ and N₂O emission factors for biofuels, the gasoline and diesel fuel emission factors from the equivalent emission technology classes are applied. CO₂ emission factors are developed according to the chemical properties of the fuel.

A3.1.4.2.6. Pipeline Transport (CRF Category 1.A.3.e.i)

Pipelines represent fossil fuel combustion engines used to power motive compressors to transport oil and natural gas products. The fuel used is primarily natural gas, but some refined petroleum, such as diesel fuel, is also used. Oil pipelines tend to use electric motors to operate pumping equipment.

Combustion-related GHG emissions associated with this equipment are calculated by applying Equation A3.1–1 to activity data and emission factors, at the provincial level for natural gas, and national level for other fuels.

A3.2. Methodology for Fugitive Emissions from Fossil Fuel Production, Processing, Transmission and Distribution

Detailed methodologies for estimating fugitive emissions from solid fuel production and the oil and gas industry are covered in this annex.

As the primary source of fugitive emissions, Canada's large oil and gas industry consists of a mix of production types, including natural gas production and processing; light, medium and heavy crude oil production; oil sands mining and extraction; and synthetic crude oil production. For a description of all sources of fugitive emissions, refer to Chapter 3.

All greenhouse gas (GHG) emissions from fuel combustion activities associated with fossil fuel exploration, production, processing, transmission and distribution are reported under the Energy Industries (section 3.2.4) and Transport (section 3.2.6) sections of Chapter 3, and their respective methodologies can be found in Annex 3.1 (sections A3.1.4.1 and A3.1.4.2).

A3.2.1. Solid Fuels

A3.2.1.1. Coal Mining

Canada Specific Coal Mining Studies

Canada's fugitive emission estimates are largely based on three studies: *Methane Emissions from Canadian Coal Operations: A Quantitative Estimate*, prepared by B. Hollingshead (1990) for the Transalta Utilities Corp.; *Management of Methane Emissions from Coal Mines: Environmental, Engineering, Economic and Institutional Implications of Options*, prepared by B. King (1994) for Neill and Gunter Ltd; and *Compilation of a National Inventory of Greenhouse Gas and Fugitive VOC Emissions by the Canadian Coal Mining Industry*, prepared by Cheminfo Services Inc. and Clearstone Engineering Ltd (Cheminfo and Clearstone, 2014) for Environment and Climate Change Canada (ECCC). These three studies contain mine-specific information upon which Canada has based its country-specific data, parameters and information regarding surface and underground mines, and they are confidential.

The Hollingshead study was commissioned by Transalta Utilities Corp., with the goal of estimating methane (CH_4) emissions from coal mines and coal combustion in Canada. The study developed, for the year 1989, estimates of fugitive emissions from underground and surface mines and combustion emissions from all coal use in Canada. As such, the emphasis of this study was not on developing emission factors (EFs) that would be usable on a yearly basis, but rather on providing a snapshot of all emissions from coal for a particular year. However, in the process of estimating these total emissions, a large amount of useful data was collected pertaining to the CH_4 composition of coal mined in Canada.

Canada has had, in most years, both underground and surface coal mines, and the method developed by King (1994) produced CH_4 emission factors for all coal types and all individual coal mines. Where possible, King employed the Canada-specific data included in the Hollingshead study, while clearly identifying and explaining this data source. King's method for surface and underground mines is a modified version of a process developed for the International Energy Agency by the Coal Industry Advisory Board (CIAB). Further discussion of some of these modifications can be found in the section below on surface mines. Prior to the 2016 submission, the EFs for CH_4 determined in the King (1994) study were used to estimate the CH_4 fugitive emissions from all 23 operational mines and from all mines abandoned after 1990 in Canada.

In 2014, ECCC awarded a contract to Cheminfo Canada and Clearstone Engineering to update the EFs for coal mines in Western Canada. The study produced new EFs for seven of the then 21 active surface mines using field tests from two sub-bituminous coal mines in central Alberta, one bituminous coal mine in northeast British Columbia and one bituminous coal mine in northwest Alberta. Results from the four tested mines were applied to three nearby mines that exploited the same coal seams and had similar geography. The mobile plume transect system (MPTS) that was employed develops a two-dimensional y-z plot of the pollutant concentration and wind profile downwind of the target source(s). The measurement system comprised: (1) a cavity ring-down spectrometer; (2) an 8-channel multiplexer sampling system; (3) an ultrasonic 3-D wind anemometer; (4) a GPS and inertial system; (5) a vehicle equipped with a vertical sampling mast; and (6) a computer and software.

The emissions model is a hybrid of Intergovernmental Panel on Climate Change (IPCC) Tier 2 and Tier 3 methodologies that depends on the availability of mine-specific data. Gross production values provided by Statistics Canada, before any cleaning and prework, is used to calculate fugitive emissions for all mine types. The associated post-mining activity emissions are accounted for in the underground and surface mining EFs. Additional details of the methodologies used to estimate the emissions from underground and surface mines are provided in their respective sections.

The EFs vary for each coal field, region and mine type, whether above or below ground.

Underground Mines

King (1994) estimated emissions for underground mines on a mine-specific basis by summing emissions from the ventilation system, degasification systems and post-mining activities. In the absence of measured data, emissions from the mine shaft ventilation system were estimated using Equation A3.2–1.

Equation A3.2–1

$$Y = 4.1 + (0.023 \times X)$$

Y = emissions of CH_4 per gross tonne of coal mined, $\text{m}^3 \text{CH}_4/\text{t}$ coal

X = depth of mine, m

Emissions from post-mining activities were estimated by assuming that 60% of the remaining coal CH_4 (after removal from the mine) is emitted to the atmosphere before combustion. If the CH_4 content of the mined coal was unknown, then 1.5 m^3/t , the global average for coals (King, 1994) was assumed. All underground mines in Canada are drift mines and have an effective depth of zero metres. Emissions from post-mining activities are included in the coal production EFs, after all quantities are converted to mass units, using a standard conversion of 0.67 $\text{kg}/\text{m}^3 \text{CH}_4$.

Between 1992 and 1999, all underground mining ceased in eastern Canada. The remaining underground mines were located in Alberta and British Columbia and were less gassy than mines in eastern Canada. Between 2015 and 2017, there were no active underground coal mines in Canada, however, the Donkin mine in Nova Scotia resumed operation in 2018.

Surface Mines

The CIAB methodology was modified to incorporate confidential Canadian and U.S. site-specific data (from King, Hollingshead and Cheminfo and Clearstone) for the three coal types mined in Canada, rather than using a generalized international data set to represent country-specific circumstances. King developed EFs by region, by mine and by coal types; the average CH_4 content of bituminous or sub-bituminous coal was 0.4 m^3/t (based on tests at 50 mines in the United States, obtained by King) and the Canada-specific CH_4 content for lignite was 0.05 m^3/t (Hollingshead, 1990), with the assumption that 60% of the gas is released before combustion. A field testing campaign to measure fugitive emissions of CH_4 , carbon dioxide (CO_2) and volatile organic compounds (VOCs) was performed on four coal mines in late February 2014:

- Sites 1 and 2: two sub-bituminous coal mines in central Alberta
- Site 3: one bituminous coal mine in northeast British Columbia
- Site 4: one bituminous coal mine in northwest Alberta

CH_4 emissions were measured remotely using a ground-based mobile plume transect system (MPTS) for area sources and tracer tests for volume and point sources (Cheminfo and Clearstone, 2014). Data from this field testing was used to modify the CH_4 emission factors of 7 of the 23 producing mines in Canada. The EFs in Table A3.2–1 incorporate these data and assumptions. In addition, the overall CH_4 emission factor uncertainty is reported in Table A2–1 category 1.B.1.a Fugitive Sources – Coal mining and Handling.

Surrounding unmined strata are a significant source of emissions from surface mines. Using Canadian mine-specific data from the Hollingshead study, King applied a high-wall adjustment to the surrounding unmined strata, to a depth of 50 m below the mining surface. Base EFs for surface mining were increased by 50% (King 1994) to account for this out-gassing adjustment and are reflected in the EFs in Table A3.2–1.

To obtain the emissions from coal mining, Equation A3.2–2 is used.

Equation A3.2–2

$$\text{Provincial Emissions} = \sum (\text{EF}_{i,j,k,l} \times \text{Coal}_{i,j,k,l})$$

$\text{EF}_{i,j,k,l}$ = the emission factor from the King (1994) or Cheminfo and Clearstone (2014) studies for province i , coal type j , mine k and coal field l

$\text{Coal}_{i,j,k,l}$ = the gross production of coal for province i , coal type j , mine k and coal field l

Emissions are calculated for each province and then summed to determine the emission estimate for Canada.

Table A3.2–1 Fugitive Emission Factors for Coal Mining, Year 2020

Area	Coal Type	Mine Type	Emission Factor	Units
NS	Bituminous	Surface	0.07	t CH ₄ / kt coal mined
SK	Lignite	Surface	0.07	t CH ₄ / kt coal mined
AB	Bituminous	Surface	0.67	t CH ₄ / kt coal mined
AB	Sub-bituminous	Surface	0.21	t CH ₄ / kt coal mined
BC	Bituminous	Surface	0.93	t CH ₄ / kt coal mined

Note: Adapted from King (1994) and Cheminfo et al. (2014).

Despite the closing of east coast underground mines, production increases at less gassy surface mines in Alberta and British Columbia have sustained Canada's total annual coal production. The net effect is that, while production has stayed steady, total fugitive emissions associated with coal mining have declined significantly since 1990.

Activity Data

The model requires the gross mine output data for each type of coal mined in each province. Until 2002, the data was obtained from Statistics Canada's *Coal and Coke Statistics* publication (Statistics Canada, 1999–2002). In 2002, the publication was discontinued, and Statistics Canada now provides this data directly to ECCC via a memorandum of understanding.

Emission Factors

EFs were developed by coal type, coal mine type and coal field. Because of confidentiality requirements, factors can only be reported at the provincial level. Therefore, weighted EFs were developed at the provincial level.

These weighted EFs for 2020, by producing mine and coal type, were developed using the King (1994), and Cheminfo and Clearstone (2014) studies and are listed in Table A3.2–1. For a complete list of coal mining fugitive EFs, see Annex 6.

3.2.1.2. Abandoned Underground Coal Mines

Coal mine methane (CMM) and other gases naturally exist within coal seams and are released to the atmosphere under suitable conditions. Of these gases, CH₄ is of greatest concern, while others releases, such as CO₂, are considered small and are not reported since the IPCC provides no method for estimating these emissions (IPCC, 2006).

As noted in A3.2.1.1, structural disturbance exposes the coal to lower atmospheric pressures, allowing the release of fugitive emissions during mining and post-mining operations, including handling, crushing and transportation. Once an underground mine closes and active venting stops, emissions may continue for decades. After production ceases, all subsequent emissions are estimated using the model described in this section.

Methodology

CMM is influenced by many factors, including geological seam structure, coal rank and characteristics, mining activities, pressure gradients, mine flooding and post-mining venting and capping. Though no Canadian data is available on post-mining venting and capping, provincial regulations require all recently abandoned mines to be capped for safety.

The IPCC Tier 2 equation for abandoned mines takes the general form in Equation A3.2–3.

Equation A3.2–3 IPCC Tier 2

$$\text{CH}_4 \text{ Emissions} = \text{Unflooded Mines} \times \text{Fraction Gassy} \times \text{Average Emission Rate} \\ \times \text{EF} \times \text{Conversion Factor}$$

CH₄ Emissions	=	yearly emissions (Gg/year)
Unflooded Mines	=	number of unflooded mines
Fraction Gassy	=	% of mines defined as gassy
Average Emission Rate	=	(m ³ /year)
EF	=	emission factor, dimensionless, of the form (1+aT)b
Conversion Factor	=	converts CH ₄ volume to mass (0.67 kg/m ³ , at 20°C and 1 atmosphere pressure)

The IPCC Tier 3 equation for abandoned mines takes the general form in Equation A3.2–4.

$$\text{CH}_4 \text{ Emissions} = (\text{Emission rate at closure} \times \text{EF} \times \text{Conversion Factor})$$

<i>CH₄ Emissions</i>	=	yearly emissions (Gg/year)
<i>Emission rate at closure</i>	=	known emission rate for specific mine (m ³ /year)
<i>EF</i>	=	emission factor, dimensionless, of the form (1+aT)b
<i>Conversion Factor</i>	=	converts CH ₄ volume to mass (0.67 kg/m ³ , at 20°C and 1 atmosphere pressure)

Detailed data on mine CH₄ emission rates during production years was only available for five mines in Nova Scotia (King 1994). This data allowed the use of Equation A3.2–4, following the IPCC Tier 3 approach, to estimate abandoned mine emissions in this region. For all other regions of Canada, known production data for abandoned mines was averaged over the life of the mines, and the EFs in Table A3.2–1 were used to estimate emissions in the final year of production. On the basis of this estimate, Equation A3.2–3 was used to calculate emissions. Calculations were done using five time intervals, which can be seen in Table A3.2–4 following the Tier 2 approach for the determination of percent gassy mines per time interval. Mines abandoned before 1900 are assumed to be non-emitting (IPCC, 2006).

Following the end of mining activities, CH₄ emissions have been shown empirically to drop off following a hyperbolic decline curve. This is modelled using the IPCC Tier 2/3 emission factor equation (1+aT)b, where a and b are mine- or basin-specific constants and T is the time since abandonment (IPCC, 2006). See Table A3.2–2 for a list of constants applied to Canadian data. This IPCC EF formula was used for all provincial estimates.

CH₄ emissions from flooding mines decrease dramatically once active pumping ceases. Water pressure inhibits CH₄ from being emitted due to reduced relative permeability. U.S. EPA empirical studies (U.S. EPA, 2004) based on U.S. mines indicate that mine flooding occurs within eight years. The 2006 IPCC Guidelines (IPCC, 2006) indicate that fully flooded mines be assigned zero emissions but be explicitly listed.

For the purposes of calculating emissions, mines are assumed unflooded unless specific data exists. Provincial experts in Alberta indicated that most mines are flooded, but had knowledge of flooding at only the Bellevue Mine Museum. Therefore, only the 12 abandoned mines in the near vicinity of the Bellevue Mine Museum—that closed over 20 years ago—were assumed flooded. For Nova Scotia, provincial experts at Nova Scotia Environment confirmed that underground mines started flooding immediately after pumps were turned off and that all mines were flooded by end of summer 2013.⁵ Table A3.2–3 characterizes the condition of abandoned mines by flooded and non-flooded, for all regions of Canada that have underground coal mines. In 2018 the Donkin mine in Nova Scotia returned to production and is no longer included in the data for abandoned mines.

The IPCC defaults in Table A3.2–4 were used to estimate the percentage of gassy mines in each region and time interval. For all regions of Canada, with the exception of Saskatchewan, the default high values for gassiness were assumed.

The lower IPCC default percentage of gassy mines was chosen for Saskatchewan mines based on time since abandonment, lignite rank, small mine size and shallow depth—often dug from a riverbed into a slight hill. Additionally, during a public safety review, all mine entrances were either capped or sealed. The non-gassy nature of these mines was previously reported in Hollingshead (1990).

Table A3.2–2 IPCC Tier 2/3 – Emission Factor Coefficients

Coal Rank	a	b
Anthracite	1.72	-0.58
Bituminous	3.72	-0.42
Sub-bituminous	0.27	-1.00

⁵ Nova Scotia Environment. 2015. Personal communication (email from Miller M, Policy Analyst, Nova Scotia Environment to Baker W, Pollutant Inventories and Reporting Division, Environment and Climate Change Canada, dated November 16, 2015).

Table A3.2–3 IPCC Tier 2/3 – Abandoned Underground Coal Mines, 2020

Region	Number of Abandoned Coal Mines ^a	Number of Abandoned Mines Flooded ^b
NS ^c	281	281
SK ^d	245	0
AB	855	13
BC	51	0
CA	1 432	294

Notes:

a. Only mines that produced more than 0.5 kilotonnes are included.

b. When no data is available, mines are assumed to be non-flooded.

c. Tier 2 and 3 estimates used for Nova Scotia.

d. Saskatchewan lignite mine estimate uses IPCC Tier 2 sub-bituminous emissions factor calculated for each time band (see IPCC 2006 4.27, Equation 4.1.12).

Table A3.2–4 IPCC Tier 2, % Gassy Mines per Time Interval

Time Interval	Low	High
1900–1925	0%	10%
1926–1950	3%	50%
1951–1975	5%	75%
1976–2000	8%	100%
2001–present	9%	100%

Activity Data

This model uses data obtained from industry and from provincial and federal government sources. The general lack of detailed data sources affected the choice of estimation methods, preventing the incorporation of likely but unconfirmed flooding and mine-specific emissions measurements. Conservative assumptions were made when accurate data was unavailable for mine gassiness, flooded status and EFs. As previously noted, in 2018, the Donkin mine in Nova Scotia returned to production and is no longer included in the data for abandoned mines.

Emissions

The results of emission calculations, for select years, are presented in Chapter 3. Abandoned mines in Nova Scotia have historically contributed the largest proportion of emissions; the two emission peaks in 1993 and 2000 correspond to closures of large mines in that province. There were two recent mine abandonments in Western Canada and the effect of these closures on the model's decline curves are visible in the latest reporting years.

A3.2.2. Oil and Natural Gas

A3.2.2.1. Upstream Oil and Natural Gas Production

Fugitive emissions from the upstream oil and gas (UOG) industry are estimated using the following methods depending on the emission source and data availability in the province or territory.

- **Direct estimation:** where possible, facility reported volumetric data and detailed gas composition data are used to directly estimate emissions. This applies to Alberta and Saskatchewan reported venting and flaring emissions (see section A3.2.2.1.2) and Alberta and British Columbia surface casing vent flow emissions (see section A3.2.2.1.4)
- **Modelled:** when facility reported data is not available, emissions are modelled using annual facility counts, average number of components per facility, component-level EFs and gas composition data. This applies to emissions from pneumatic devices, compressor seals, and equipment leaks in British Columbia, Alberta, Saskatchewan and Manitoba (see section A3.2.2.1.3)
- **Interpolated/Extrapolated:** detailed inventory studies for the years 2000, 2005, and 2011 are used as the basis to interpolate/extrapolate emissions for years without detailed inventory data based on changes in various activity data. This applies to all other fugitive emission sources and provinces and territories not mentioned above (see section A3.2.2.1.1)

Table A3.2–5 lists the emission sector categories and fugitive sources estimated and the allocation of these emissions according to the Common Reporting Format (CRF) categories.

Table A3.2–5 Allocation of Upstream Oil and Gas Inventory Emissions to CRF Fugitive Categories

	Emission Sector Categories	Emission Source Categories
1.B.2.a.2 Oil – Production	Light/Medium Crude Oil Production	Fugitive Equipment Leaks; Loading/Unloading; Storage Losses; Surface Casing Vent Flow
	Heavy Crude Oil Cold Production	Fugitive Equipment Leaks; Loading/Unloading; Storage Losses; Surface Casing Vent Flow
	Well Servicing	Fugitive Equipment Leaks; Loading/Unloading; Storage Losses
	Heavy Crude Oil Thermal Production	Fugitive Equipment Leaks; Loading/Unloading; Storage Losses; Surface Casing Vent Flow
	Well Testing	Fugitive Equipment Leaks; Loading/Unloading; Storage Losses
	Disposal and Waste Treatment	Fugitive Equipment Leaks
1.B.2.a.3 Oil – Transport	Petroleum Liquids Transportation	Fugitive Equipment Leaks; Storage Losses
1.B.2.b.2 Natural Gas – Production	Natural Gas Production	Fugitive Equipment Leaks; Loading/Unloading; Storage Losses; Surface Casing Vent Flow
1.B.2.b.3 Natural Gas – Processing	Natural Gas Processing	Fugitive Equipment Leaks; Loading/Unloading; Storage Losses
1.B.2.b.4 Natural Gas – Transmission and Storage	Gas Transmission; Gas Storage	Fugitive Equipment Leaks; Spills/Pipeline Ruptures
1.B.2.b.5 Natural Gas – Distribution	Gas Distribution	Fugitive Equipment Leaks; Spills/Pipeline Ruptures
1.B.2.b.6 Natural Gas – Other – Accidents and Equipment Failures	Accidents and Equipment Failures	Surface Casing Vent Flow/Gas Migration; Spills/Pipeline Ruptures
1.B.2.c.1.i Venting – Oil	Light/Medium Crude Oil Production	Glycol Dehydrator Off-Gas; Reported Venting; Unreported Venting
	Heavy Crude Oil Cold Production	Glycol Dehydrator Off-Gas; Reported Venting; Unreported Venting
	Heavy Crude Oil Thermal Production	Glycol Dehydrator Off-Gas; Reported Venting; Unreported Venting
	Petroleum Liquids Transportation	Reported Venting; Unreported Venting
1.B.2.c.1.ii Venting – Natural Gas	Natural Gas Production	Glycol Dehydrator Off-Gas; Reported Venting; Unreported Venting
	Natural Gas Processing	Glycol Dehydrator Off-Gas; Formation CO ₂ ; Reported Venting; Unreported Venting
	Gas Transmission	Reported Venting
	Gas Distribution	Glycol Dehydrator Off-Gas; Reported Venting; Unreported Venting
	Gas Storage	Reported Venting; Unreported Venting
1.B.2.c.1.iii Venting – Combined	Well Drilling; Well Servicing	Reported Venting
	Well Testing	Glycol Dehydrator Off-Gas; Reported Venting; Unreported Venting
	Disposal and Waste Treatment	Unreported Venting
1.B.2.c.2.i Flaring – Oil	Light/Medium Crude Oil Production; Heavy Crude Oil Production; Heavy Crude Oil Thermal Production; Petroleum Liquids Transportation	Flaring
1.B.2.c.2.ii Flaring – Natural Gas	Natural Gas Production; Natural Gas Processing; Gas Transmission; Gas Storage; Gas Distribution	Flaring
1.B.2.c.2.iii Flaring – Combined	Well Drilling; Well Servicing; Well Testing; Disposal and Waste Treatment	Flaring

A3.2.2.1.1. UOG and CAPP Study

Except where otherwise noted, fugitive emissions from the UOG industry are based on two separate studies: a study titled *A National Inventory of Greenhouse Gas, Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H₂S) Emissions by the Upstream Oil and Gas Industry* (CAPP, 2005a), prepared by Clearstone Engineering Ltd. for the Canadian Association of Petroleum Producers (CAPP) and referred to hereafter as the CAPP study, and an update to the inventory that was completed in 2014 for Environment Canada by Clearstone Engineering Ltd. and referred to hereafter as the UOG study (EC, 2014). Both inventories used an IPCC Tier 3 bottom-up assessment to estimate all GHG emissions from the UOG sector, with the exclusion of oil sands mining, extraction and upgrading. The CAPP study provided a detailed emission inventory for the year 2000, while the UOG study produced inventories for the years 2005 and 2011.

In general, the emission inventories for the years 2000, 2005 and 2011 were used directly, except for a few special cases. If a specific source did not exist in one of the inventory years (e.g. the 2000 inventory) due to insufficient data, but did exist in another inventory year (e.g. the 2005 inventory), then emissions for that particular source were extrapolated from the known year and included in the inventory that was missing data to ensure completeness. A brief description of the methodology used in the CAPP and UOG studies follows, along with the methodology used to estimate the emissions for 1990–1999, 2001–2004, 2006–2010 and from 2012 onwards.

Methodology for the 2000, 2005 and 2011 Estimates

The emission estimates contained in the CAPP and UOG studies were developed using a bottom-up approach, beginning at the individual facility and process unit level and aggregating the results to provide emission estimates by facility and geographic area. The Canadian UOG sector's assets and operations are vast: the 2011 inventory included over 300 000 capable oil and gas wells, 14 100 batteries producing gas into more than 5000 gathering systems delivering to almost 750 gas plants, and 24 000 oil batteries delivering to 150 tank terminals, all of which are interconnected by tens of thousands of kilometres of pipeline carrying hydrocarbons from wells to batteries to plants to markets.

Emissions from flaring, venting, equipment leaks, formation CO₂ venting, storage losses, loading/unloading losses and accidental releases were estimated. The basic methods used to estimate GHG emissions were:

- emission monitoring results
- emission source simulation results
- emission factors
- destruction and removal efficiencies

In order to estimate emissions, large amounts of data were collected including:

- measured volumes of natural gas taken from the process
- vented and flared waste gas volumes
- fuel purchases (propane, diesel fuel, etc.)
- fuel analyses
- emission monitoring results
- process operating conditions that may be used to infer the work being done by combustion devices (gas compositions, temperatures, pressures and flows, etc.)
- spill and inspection reports

Other required data included the following:

- types of processes being used
- equipment inventories
- emission source control features
- sulphur content of the fuels consumed and waste gas flared
- composition of the inlet and outlet streams

Refer to the CAPP study (CAPP, 2005a) and UOG study (EC, 2014) for further details.

Methodology for Extrapolating Emission Estimates

The method for extrapolating emissions from a known inventoried year to other non-inventoried years was developed by Clearstone Engineering Ltd. (CAPP, 2005b). This method was used to backcast the 2000 emission estimates for the 1990–1999 time period, to extrapolate the 2011 inventory for 2012 onwards and, in conjunction with other curve fitting methods, to interpolate the 2001–2004 and 2006–2010 time periods.

Equation A3.2–5 is used to estimate emissions for non-inventoried years by multiplying base year emissions data for a given source and sector by the ratio of activity data for the non-inventoried year to that of the base year. Various types of activity data for each province/territory and year were used, such as natural gas and crude oil production volumes, fuel, flare and vent volumes, number of wells drilled, number of spills, ruptures and blowouts, total capable oil and gas wells, and shrinkage. Not all activity data is available for all years or all regions. Emission sources for specific sectors and regions were extrapolated using the most appropriate activity data. Where activity data was not available for the entire time series, the methodology to interpolate intermediate years, which is described later in this section, was used to provide one consistent time series.

Table A3.2–6 lists the publicly available activity data used to extrapolate emissions along with the corresponding data source. Table A3.2–7 contains a list of the activity data used to estimate flaring emissions for each region, sector category and time period while Table A3.2–8 contains the same information for reported venting. Table A3.2–9 displays the activity data that is used to extrapolate emissions for all other UOG fugitive sources such as fugitive equipment leaks, unreported venting,⁶ storage losses, etc.

⁶ Unreported venting includes 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.

Table A3.2–6 Required Activity Data and Their Sources

Publisher	Publication	Activity Data
Alberta Energy Regulator (AER)	ST60B: Upstream Petroleum Industry Flaring and Venting Report (AER, 2020a)	Reported venting and flaring volumes
	ST3: AER Industries Monthly Statistics, Gas Supply and Disposition (AER, 2021a)	Shrinkage
	Alberta's Energy Reserves and Supply/Demand Outlook (AER, 2021b)	In-situ bitumen production
	AER Compliance Dashboard (AER, 2021c)	Number of incidents
British Columbia Government	Production and distribution of natural gas (BC, 2019)	Reported venting volumes
		Shrinkage
British Columbia Oil and Gas Commission	Drilling Kicks and Blowouts by Area (BCOGC, 2021a)	Sum of kicks and blowouts
	Air Summary Report (BCOGC, 2019)	Reported flaring volumes
	Petrinex Volumetric data (BCOGC, 2021b)	Reported venting and flaring volumes Shrinkage
Canada Energy Regulator (CER)	Canada's Energy Future (CER, 2021)	Non-associated gas production
Canada-Newfoundland and Labrador Offshore Petroleum Board (CNLOPB)	Development Wells—Hebron (CNLOPB, 2021a)	Number of capable wells
	Development Wells—Hibernia (CNLOPB, 2021b)	Number of capable wells
	Development Wells—North Amethyst (CNLOPB, 2021c)	Number of capable wells
	Development Wells—Terra Nova (CNLOPB, 2021d)	Number of capable wells
	Development Wells—White Rose (CNLOPB, 2021e)	Number of capable wells
	Environment Statistics—Spill Frequency and Volume Annual Summary (CNLOPB, 2021f)	Number of spills
	Monthly Gas Flaring (CNLOPB, 2021g)	Reported flaring volumes
Canadian Association of Petroleum Producers (CAPP)	Statistical Handbook for Canada's Upstream Petroleum Industry (CAPP, 2021)	Total wells drilled (including dry and service) (Tables 1.2b—1.2f) Sum of Operated Oil Wells (Table 3.17a) and Operated Gas Wells (Table 3.18a)
Manitoba Government	Petroleum Industry Spill Statistics (MB, 2021a)	Number of spills
New Brunswick Natural Resources and Energy Development	Monthly Production Statistics (NB NRED, 2021a)	Light/medium crude oil production Natural gas production
Saskatchewan Ministry of Energy and Resources	Crude Oil Volume and Value Summary (SK MER, 2012–2020a)	Light/medium crude oil production Heavy crude oil production
	Natural Gas Volume and Value Summary (SK MER, 2012–2020b)	Non-associated gas production
	Saskatchewan Fuel, Flare and Vent (SK MER, 2012–2020c)	Reported flaring and venting volumes
	Saskatchewan Upstream Oil and Gas IRIS Incident Report (SK MER, 2021a)	Number of spills
	Saskatchewan Annual Petroleum Statistics (SK MER, 2009–2011)	Reported flaring and venting volumes Shrinkage
	Saskatchewan Mineral Statistics Yearbook, Petroleum and Natural Gas. (SK MER, 1990–2008)	Reported flaring and venting volumes Shrinkage
Statistics Canada	Table 25-10-0047-01 (formerly CANSIM 131-0001) Natural gas, monthly supply and disposition (Statistics Canada, n.d.[a])	Gross production Field flared and waste Field disposition and usage Gathering system disposal and use Plant uses Shrinkage
	Table 25-10-0055-01 (formerly CANSIM 131-0004) Supply and disposition of natural gas, monthly (Statistics Canada, n.d.[b])	Gross withdrawals
	Table 25-10-0014-01 (formerly CANSIM 126-0001) Crude oil and equivalent, monthly supply and disposition (Statistics Canada, n.d.[c])	Heavy crude oil production Light/medium crude oil production Synthetic crude oil production Crude bitumen production
	Table 25-10-0063-01 (formerly CANSIM 126-0003) Supply and disposition of crude oil and equivalent (Statistics Canada, n.d.[d])	Heavy crude oil production Light/medium crude oil production Synthetic crude oil production Non-upgraded production of crude bitumen
	Report on Energy Supply and Demand in Canada (Statistics Canada, 1990–)	Total RPP Retail Pump Sales

Equation A3.2-5

$$ER_{ij}^k = ER_{ij}^{baseYr} \times \left(\frac{AF_j^k}{AF_j^{baseYr}} \right)$$

ER_{ij}^k	=	emission rate of compound i , source j , and year k , t/year
ER_{ij}^{baseYr}	=	base year (e.g. 2011) emission rate for compound i and source j , t/year
AF_j^k	=	activity factor for source j and year k
AF_j^{baseYr}	=	base year (e.g. 2011) activity factor for source j

The emissions for 1990–1999 were backcast by sector and source at the provincial level based on the year 2000 emission estimates from the CAPP study (CAPP, 2005a). The only exception to this was the province of Nova Scotia, which from 1992 to 1999 was an oil-only producing province. In 2000, it switched to a gas-only producing province. As such, the year 2000 data could not be used to estimate emissions for the 1990–1999 time period, and Nova Scotia's fugitive emissions were extrapolated based on CAPP's 1995 UOG study data (CAPP, 1999). Refer to the UOG study (CAPP, 2005a) for further details.

The emissions from 2012 onwards were extrapolated using emissions by sector and source at the provincial/territorial level based on the year 2011 emission estimates from the UOG study (EC, 2014).

Methodology for 2001–2004 and 2006–2010

In order to estimate emissions for the 2001–2004 and 2006–2010 time periods, all three base year inventories (2000, 2005 and 2011) were extrapolated for the 2000–2011 time period using the method described previously. This resulted in three curves which were used to interpolate the intermediate years by using either a “wedging” or “proportional adjustment” method, depending on the circumstance. The “wedging” method was used unless it resulted in negative emission estimates for any year in the time period. Less than 0.3% of cases required the use of the “proportional adjustment” method.

Table A3.2-7 Activity Data Used to Extrapolate Flaring Emissions by Region and Year

Region	Emission Sector Category	Time Period	Activity Data	Time Period	Activity Data	
AB	Light/Medium Crude Oil Production	1990–2000	Field flared and waste	2000–2009	Flaring – Oil batteries	
	Heavy Crude Oil Cold Production				Flaring – Oil batteries + Bitumen batteries	
	Heavy Crude Oil Thermal Production				Flaring – Bitumen batteries	
	Natural Gas Production				Flaring – Gas batteries + Gas gathering systems	
	Natural Gas Processing				Flaring – Gas plants	
	Well Testing				Flaring – Well testing	
	Petroleum Liquids Transportation				Flaring – Total	
	Disposal and Waste Treatment				Flaring – Total	
BC	Light/Medium Crude Oil Production	1990–1995	Field flared and waste	1996–2020	Flaring – Solution Gas	
	Natural Gas Production				Flaring – Production Facilities	
	Natural Gas Processing				Flaring – Gas Processing Plants	
	Well Testing		Wells Drilled		Flaring – Well Cleanup and Testing	
	Well Drilling				Flaring – Underbalanced Drilling	
SK	Heavy Crude Oil Thermal Production	1990–2000	Field flared and waste	2001–2011	Flaring – Heavy Oil	
NL	Light/Medium Crude Oil Production	1997–2020	Total flaring			
MB, NB, NT	Light/Medium Crude Oil Production	1990–2020	Light/medium crude production			
NB, NS, ON, YT	Natural gas production	1990–2020	Natural gas production			
NT	Natural gas processing	1990–2020	Field flared and waste			
NS, ON	Natural gas processing	1990–2020	Natural gas production			
BC, ON, SK	Petroleum Liquids Transportation	1990–2020	Total crude production			
AB	Well Servicing	1990–2020	Wells Drilled			
SK	Well Testing	1990–2020	Wells Drilled			

Table A3.2-8 Activity Data Used to Extrapolate Reported Venting Emissions by Region and Year

Region	Emission Sector Category	Time Period	Activity Data	Time Period	Activity Data
AB	Light/Medium Crude Oil Production	1990–2000	Light/medium crude production	2000–2009	Venting – Oil batteries
	Heavy Crude Oil Cold Production		Heavy crude production		Venting – Oil batteries + Bitumen batteries
	Heavy Crude Oil Thermal Production		In-situ thermal production		Venting – Bitumen batteries
	Natural Gas Production		Natural gas production		Venting – Gas batteries + Gas gathering systems
	Natural Gas Processing		Natural gas production		Venting – Gas plants
	Well Testing		Wells drilled		Venting – Well testing
	Petroleum Liquids Transportation		Total crude production		Venting – Total
BC	Light/Medium Crude Oil Production	1990–2011	Light/medium crude production	2011–2020	Field vented
	Natural Gas Production		Natural gas production		Field vented
	Natural Gas Processing		Natural gas production		Natural gas production
SK	Heavy Crude Oil Cold Production	1990–2005	Heavy crude production	2005–2011	Venting – Heavy oil
	Heavy Crude Oil Thermal Production		Heavy crude production		Venting – Heavy oil
MB	Light/Medium Crude Oil Production	1990–2020	Light/medium crude production		
NT	Natural gas processing	1990–2020	Natural gas production		
AB, SK, BC	Well Servicing, Well Drilling	1990–2020	Wells Drilled		

Wedging

The “wedging” method evenly distributes the difference in emissions for a given source and sector in a given province between an inventoried year and an extrapolated year to maintain the emissions trend using Equation A3.2–6.

Equation A3.2–6

$$ER_{ij}^k = ER_{ij}^{k,k1_exp} + \frac{(ER_{ij}^{k2_inv} - ER_{ij}^{k2,k1_exp})}{(k2 - k1)} \times (k - k1)$$

ER_{ij}^k	=	emission rate of compound i , source j , and year k
$ER_{ij}^{k,k1_exp}$	=	emission rate of compound i and source j from extrapolated year $k1$ data
$ER_{ij}^{k2_inv}$	=	emission rate of compound i and source j from inventoried year $k2$ data
$ER_{ij}^{k2,k1_exp}$	=	emission rate of compound i , source j and year $k2$ from extrapolated year $k1$ data
k	=	year between $k1$ and $k2$
$k1$	=	base year 1 (e.g. 2000 or 2005)
$k2$	=	base year 2 (e.g. 2005 or 2011)

If $k1$ is equal to 2005, $k2$ is equal to 2011, and k is equal to $k1$, then the result of Equation A3.2–6 is the emission rate from the 2005 inventoried year. This occurs since the 2005 extrapolated data uses the 2005 inventoried year as is for the year 2005. If k is equal to $k2$, then the result is the emission rate from the 2011 inventoried year. This shows that this method will maintain the emission estimates for the inventoried years, while interpolating the intermediate years and maintaining the emissions trend.

Figure A3.2–1 shows the results of the “wedging” method in graphical form. In general, the 2000 and 2005 inventory years are used to interpolate emissions by sector, source and province/territory for the 2001–2004 time period, while the 2005 and 2011 inventory years are used to interpolate emissions for the 2006–2010 time period. However, there are a few special cases where the 2000 and 2011 inventory years are used to interpolate emissions for the 2001–2010 time period. This occurs when data was missing or incomplete for the 2005 data year and, as a result, specific sector, source and province/territory combinations were not able to be estimated for the 2005 inventory. In addition, on the basis of conversations with the contractor and the province of Saskatchewan, the Saskatchewan venting emissions

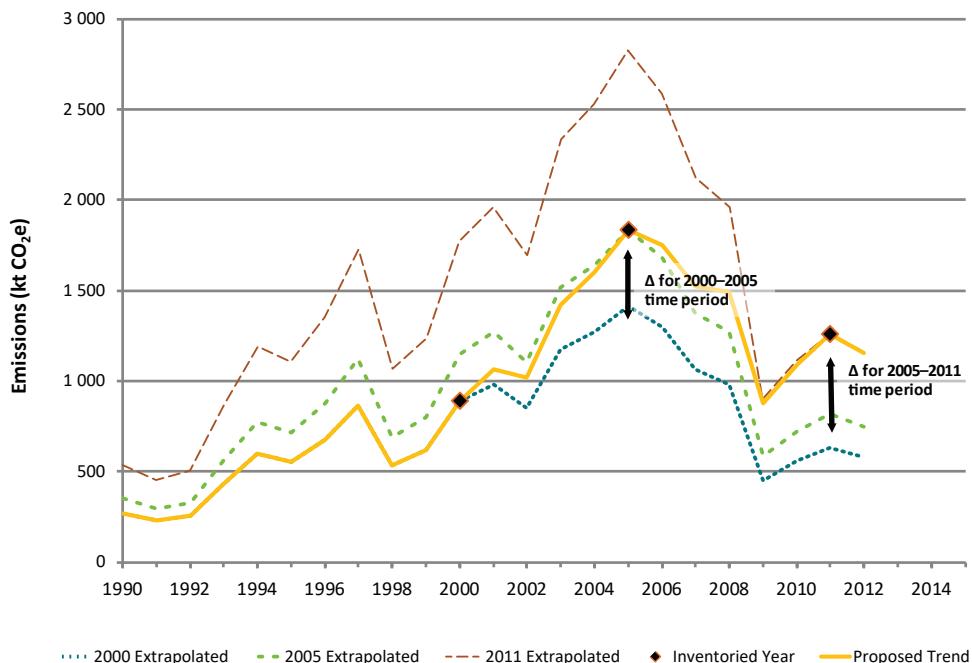
for the cold production heavy crude oil sector in the 2005 inventory were determined to be unreliable. As a result, emissions for this source and sector were interpolated using the 2000 and 2011 data as end points with the 2005 data point being omitted.

Finally, if any specific source and sector in a given province/territory only existed in one of the inventoried years, then the inventoried data was extrapolated for the entire time series. All of this was done to ensure time-series consistency.

Table A3.2–9 Activity Data Used to Extrapolate Other Fugitive Emissions by Region for All Years

Emission Sector Category	Emission Source Category	Region	Activity Data
Accidents and Equipment Failures	Spills/Pipeline Ruptures	All	Total number of spills, ruptures and blowouts
Accidents and Equipment Failures	Gas Migration	All	Total number of capable oil and gas wells
Accidents and Equipment Failures	Surface Casing Vent Flow	MB, NL, NS, NT, ON, SK, YT	Total number of capable oil and gas wells
Light/Medium Crude Oil Production	Fugitive Equipment Leaks	NB, NL, NS, NT, ON	Light/medium crude oil production
	Unreported Venting – pneumatics Unreported Venting – compressor seals	All	Light/medium crude oil production
Heavy Crude Oil Cold Production	Glycol Dehydrator Off-Gas Loading/Unloading Storage Losses Other Unreported Venting	AB, SK	Heavy crude oil production
Heavy Crude Oil Thermal Production	Fugitive Equipment Leaks	AB	In-situ bitumen production
	Glycol Dehydrator Off-Gas Loading/Unloading Storage Losses Unreported Venting	SK	Heavy crude oil production
Natural Gas Production	Fugitive Equipment Leaks	NB, NL, NS, NT, ON, YT	Natural gas production
	Unreported Venting – pneumatics		
	Unreported Venting – compressor seals	AB, BC, SK	Non-associated gas production
Natural Gas Processing	Glycol Dehydrator Off-Gas Loading/Unloading Storage Losses	All other provinces	Natural gas production
	Other Unreported Venting		
	Formation CO ₂	All	Shrinkage
Disposal and Waste Treatment	Fugitive Equipment Leaks Storage Losses Unreported Venting	AB	Total crude production
Petroleum Liquids Transportation	Fugitive Equipment Leaks	PE and QC	Total RPP Retail Pump Sales
	Storage Losses Unreported Venting	All other provinces	Total crude production
Well Servicing Well Testing	Fugitive Equipment Leaks Glycol Dehydrator Off-Gas Storage Losses Loading/Unloading Unreported Venting	All	Wells drilled
Gas Storage	Fugitive Equipment Leaks Unreported Venting	All	Natural gas delivered to and received from storage
Gas Transmission Gas Distribution	Fugitive Equipment Leaks Glycol Dehydrator Off-Gas Spills/Pipeline Ruptures Unreported Venting	All	Kilometres of pipeline

Figure A3.2-1 Graphical Representation of the “Wedging” Method



Proportional Adjustment

As stated previously, if the “wedging” method resulted in negative emissions in any year of the interpolation time period, then the method was abandoned for that given sector, source and province/territory and the “proportional adjustment” method was used, as shown in Equation A3.2-7.

Equation A3.2-7

$$ER_{i,j}^k = ER_{i,j}^{k,k1_exp} \times \frac{(ER_{i,j}^{k2_inv})}{(ER_{i,j}^{k2,k1_exp})}$$

$ER_{i,j}^k$	=	emission rate of compound i , source j , and year k
$ER_{i,j}^{k,k1_exp}$	=	emission rate of compound i and source j from extrapolated year $k1$ data
$ER_{i,j}^{k2_inv}$	=	emission rate of compound i and source j from inventoried year $k2$ data
$ER_{i,j}^{k2,k1_exp}$	=	emission rate of compound i , source j and year $k2$ from extrapolated year $k1$ data
k	=	year between $k1+1$ and $k2$
$k1$	=	base year 1 (e.g. 2000 or 2005)
$k2$	=	base year 2 (e.g. 2005 or 2011)

If $k1$ is equal to 2005, $k2$ is equal to 2011 and k is equal to $k2$, then the result of Equation A3.2-7 is the emission rate of the inventoried year for 2011. Otherwise, the emission rate of the extrapolated data is modified by the same percentage for each year in the interpolated time period. This method was required in less than 0.3% of all cases and was generally only required for sources with very low emissions.

A3.2.2.1.2. Alberta and Saskatchewan Reported Venting and Flaring

Methodology

Reported venting and flaring emissions from 2010 onwards for the province of Alberta and from 1990 onwards for the province of Saskatchewan are estimated directly instead of extrapolated from the CAPP and UOG studies (CAPP, 2005a; EC, 2014).

Reported volumes of gas flared and vented by operator and facility from the Petrinex reporting system (Petrinex, 2021) are used in conjunction with gas composition data by Alberta township (Tyner and Johnson, 2020) to estimate emissions for Alberta. However, the public Petrinex data (2021) does not include confidential facilities. *ST60B: Upstream Petroleum Industry Flaring and Venting Report* (AER, 2020a) is published annually by the Alberta Energy Regulator (AER) and summarizes reported venting and flaring volumes including those volumes reported by facilities not available in the public Petrinex data. In order to accurately reflect the complete volume of gas vented and flared, gas volumes and associated emissions are adjusted so that volumes match those reported in ST60B. Note that confidential facilities generally account for about 1-2% of reported flare and vent volumes.

Saskatchewan fuel, flare and vent volumes reported to Petrinex from 2012 onwards are summarized by the Saskatchewan Ministry of Energy and Resources (SK MER) and made available annually (SK MER, 2012–2020c). Data for years prior to 2012 are available from alternate publications (SK MER, 1990–2008; 2009–2011). Gas composition data by production class (SK MER, 2021b) are used in conjunction with the reported flare and vent volumes to estimate emissions for Saskatchewan.

Activity Data

The Petrinex reporting system collects various volumetric production accounting data for the primary purpose of collecting royalties. Oil and gas facilities in Alberta and Saskatchewan must report various data to Petrinex on a monthly basis. This data includes tombstone data for each facility such as FacilityID, subtype classification, facility name, operator, geographic location, etc. as well as volumetric data corresponding to a specific ProductID (e.g. crude oil, crude bitumen, heavy oil, water, gas, etc.) and ActivityID (e.g. flare, vent, fuel, production, receipts, disposition).

The Alberta Township Survey (ATS) system follows the Dominion Land Survey (DLS) method, whereby any parcel of land in Western Canada can be located by its legal land description. In the ATS, land is designated as being west of the 4th, 5th, or 6th Meridians (110° , 114° , 118° west longitude, respectively). Six-mile-wide columns between meridians are called ranges and are numbered consecutively from east to west. Townships are six-mile-wide rows that intersect ranges and are numbered consecutively from south to north. The term township also describes the six-by-six mile square formed by the intersection of ranges and townships. Townships are further sub-divided into 36 sections, and sections are then divided into quarters (NE, NW, SE, SW), or into 16 legal subdivisions (LSD), as indicated in Figure A3.2–2.

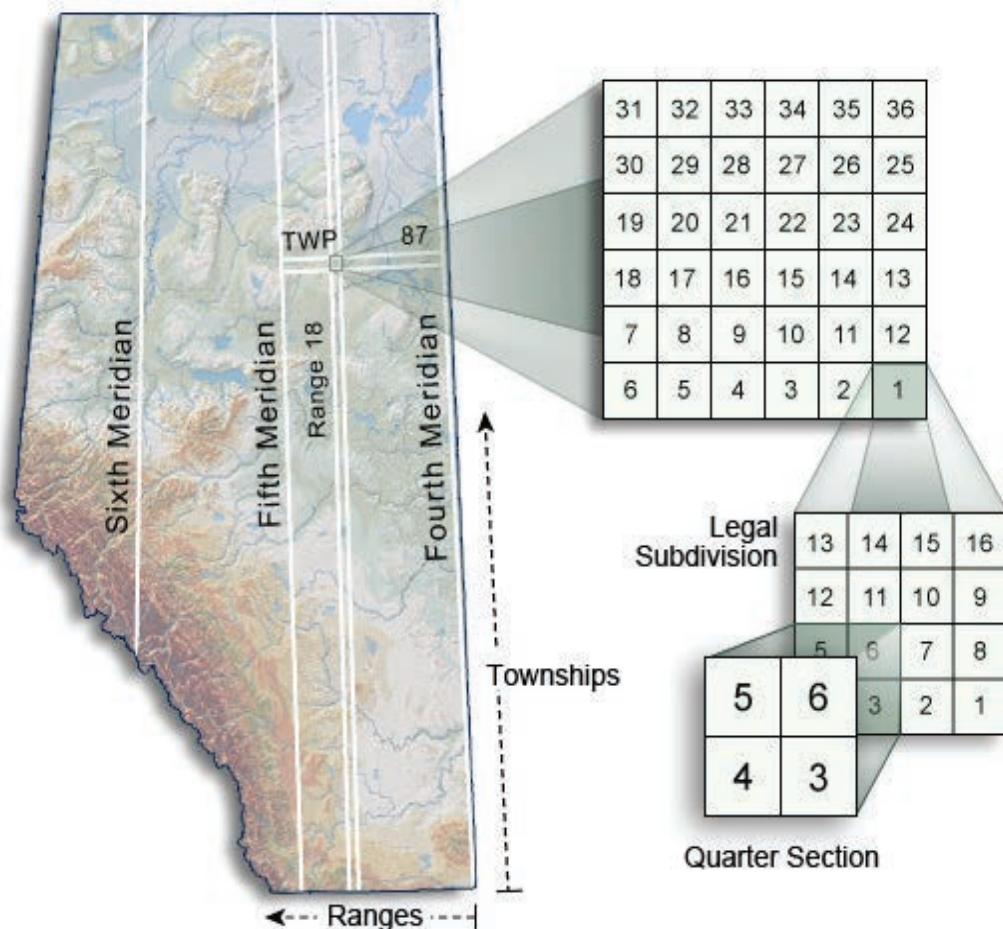
The province of Saskatchewan also uses the DLS method to define parcels of land. Saskatchewan townships are aggregated into four main petroleum and natural gas production areas: AREA I – Lloydminster, AREA II – Kindersley, AREA III – Swift Current, and AREA IV – Estevan (see Figure A3.2–3).

While detailed Saskatchewan facility-level flare and vent volumes are available from 2012 onwards (SK MER, 2012–2020c), data from 1990–2011 is provided as aggregate provincial totals (SK MER, 1990–2008; 2009–2011). However, in order to utilize the detailed composition data, the aggregated flare and vent volumes must be disaggregated to the four production areas. This was done by calculating the ratio of flare and vent volumes to production volumes for the years with detailed data (i.e. 2012–2020) and then applying those ratios to the reported production volumes by year and production area (SK MER, 1990–2008; 2009–2011) in the earlier part of the time series. The resultant flare and vent volumes were then normalized to the reported provincial flare and vent volume totals to ensure the estimated volumes were not above or below the reported data.

Vent volumes for gas gathering and gas processing were not reported until 2012. Therefore, the estimated volumes were not normalized to the reported volumes between 1990 and 2011 since they did not exist. Similarly, reported vent volumes at oil facilities were unrealistically low in comparison to production volumes from 1990 to 2006. As such, estimated volumes were not normalized to the reported volumes for this time period.

Additionally, historical heavy oil production volumes do not delineate between thermal production and heavy oil production. Because of the lack of detailed production data for the earlier part of the time series, 1990–2011 flaring emissions for heavy crude oil thermal production are still based on the method described in section A3.2.2.1.1. Likewise, 1990–2011 venting emissions for heavy crude oil thermal production and heavy crude oil cold production are also based on the A3.2.2.1.1 method.

Figure A3.2–2 Alberta Township System (ATS)



Notes :

TWP = Townships

Source = Government of Alberta (2021)

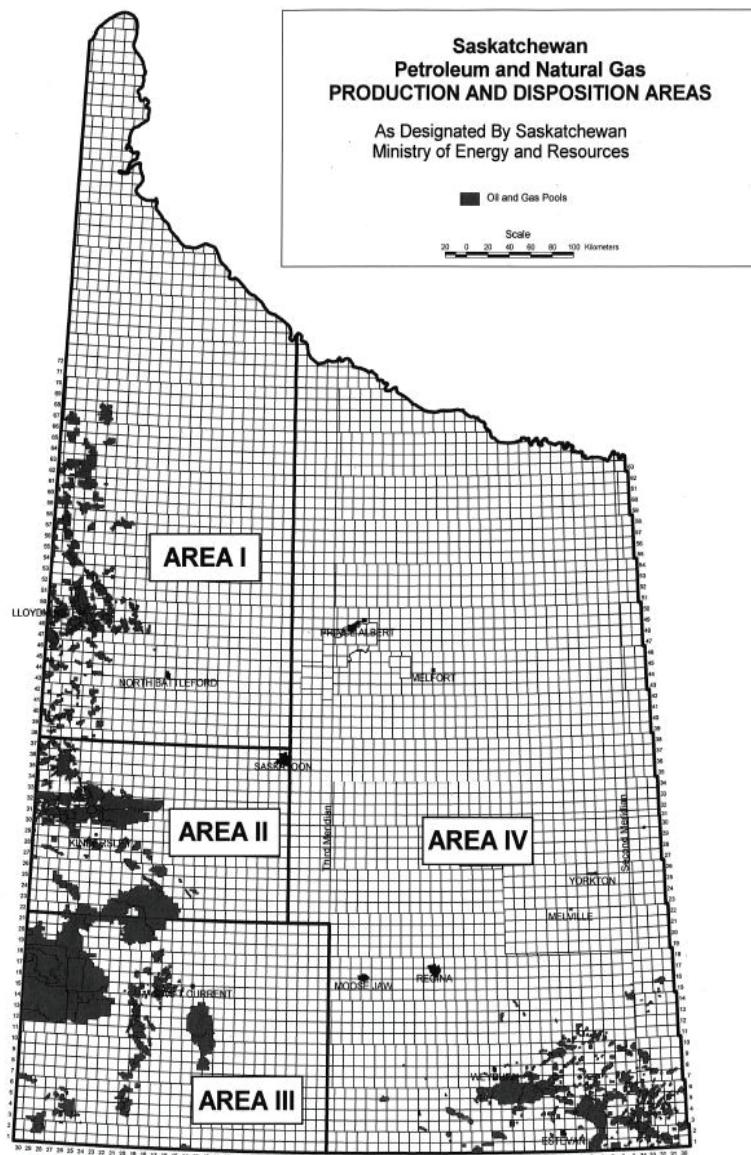
Emission Factors

In order to reflect the regional variability in gas composition, emissions for flaring and reported venting in Alberta are estimated using recently developed natural gas composition data for the UOG industry in Alberta by the Energy and Emissions Research Laboratory (EERL) of Carleton University (Tyner and Johnson, 2020) (hereafter referred to as EERL study). The EERL study uses measured gas composition data from approximately 400 000 wells in Alberta taken over a span of several decades across the province's many oil and gas producing regions to generate gas compositions by Alberta township (see Figure A3.2–4).

Gas composition data for Saskatchewan was provided directly by the Saskatchewan Ministry of Energy and Resources (SK MER, 2021b). Compositions are broken down by production class as presented in Table A3.2–10.

CO_2 , CH_4 and Nitrous oxide (N_2O) emission factors for flaring are calculated using the gas composition data as shown in Equation A3.2–8, Equation A3.2–9, and Equation A3.2–10, respectively. The calculated EFs are then multiplied by the volumetric data (Petrinex, 2020; SK MER, 2012–2021c) to estimate emissions. Similarly, CO_2 and CH_4 emissions from reported venting are estimated using Equation A3.2–11.

Figure A3.2-3 Saskatchewan Oil and Natural Gas Production Areas



Note:

Source = Government of Saskatchewan (2021)

Equation A3.2-8

$$EF_{CO_2,i} = \sum_j \frac{y_{ij} \times n_{cj} \times MW_{CO_2}}{V_{STP}} \times g_c$$

$EF_{CO_2,i}$	=	CO_2 emission factor for flaring in AB township or SK production class i (g/m^3)
y_{ij}	=	mole fraction of component j in AB township or SK production class i
n_{cj}	=	number of carbon atoms per molecule of component j
MW_{CO_2}	=	molecular weight of CO_2 (g/mol) = 44.010 g/mol
V_{STP}	=	volume of gas at standard conditions (101.325 kPa and 15°C) = 23.6444813 $m^3/kmol$
g_c	=	constant of proportionality = 1000 mol/kmol

Figure A3.2-4 Methane Content by Alberta Township with Select Oil and Gas Producing Formations

A
3

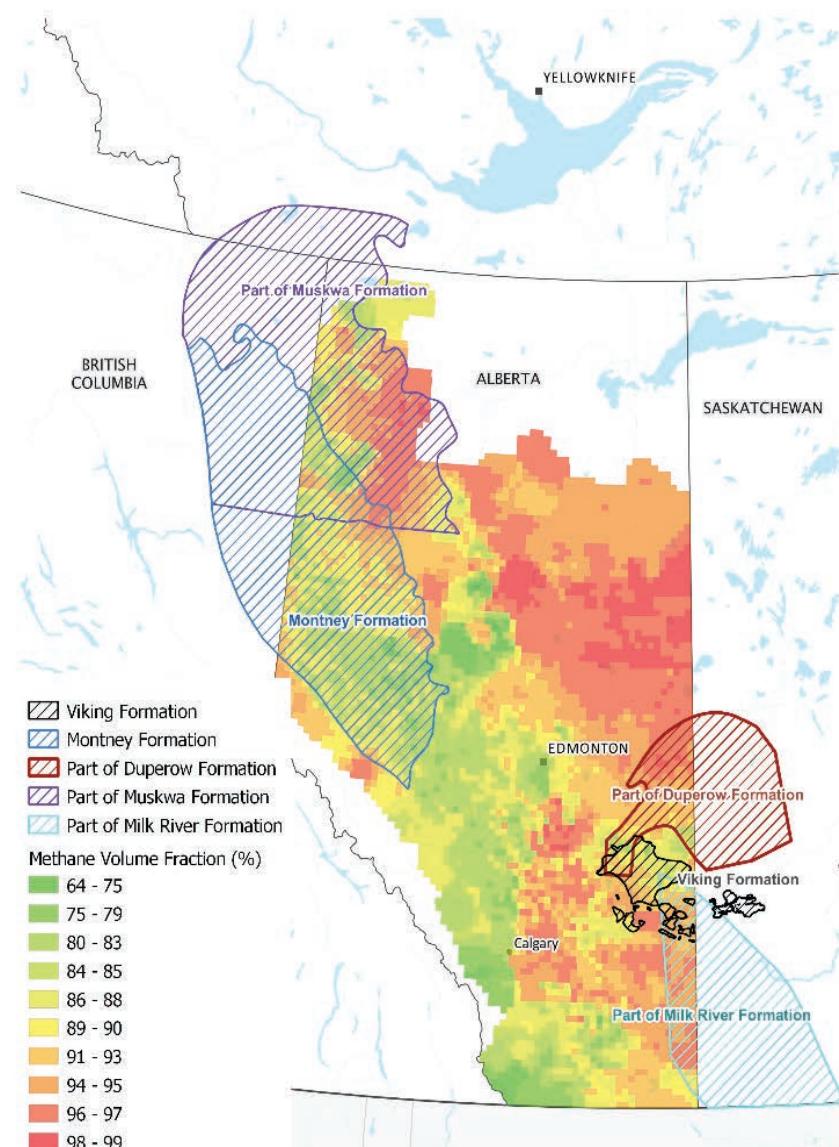


Table A3.2-10 Average Natural Gas Compositions by Saskatchewan Production Class

Saskatchewan Production Class	CH_4	CO_2	H_2S	C_2H_6	VOC	Density (kg/m^3)
	Mass Percent					
AREA I – Lloydminster	87.98	4.56	0.02	1.31	0.95	0.7233
AREA II – Kindersley Heavy	82.72	2.04	0.54	3.82	7.84	0.7559
AREA II – Kindersey Non-Heavy	67.22	0.33	0.00	3.15	24.23	0.8597
AREA III – Swift Current	66.68	2.50	0.42	2.47	17.98	0.8512
AREA IV – Estevan	35.55	2.55	1.82	17.59	36.17	1.1037

Equation A3.2-9

$$EF_{CH_4,i} = \frac{y_{CH_4,i} \times MW_{CH_4} \times (1 - CE)}{V_{STP}} \times g_c$$

$EF_{CH_4,i}$	=	CH ₄ emission factor for flaring in AB township or SK production class <i>i</i> (g/m ³)
$y_{CH_4,i}$	=	mole fraction of CH ₄ in AB township or SK production class <i>i</i>
MW_{CH_4}	=	molecular weight of CH ₄ (g/mol) = 16.04206 g/mol
CE	=	combustion efficiency = 0.98 (EC, 2014)
V_{STP}	=	volume of gas at standard conditions (101.325 kPa and 15°C) = 23.6444813 m ³ /kmol
g_c	=	constant of proportionality = 1000 mol/kmol

Equation A3.2-10

$$EF_{N_2O,i} = ER_{N_2O} \times HHV_i$$

$EF_{N_2O,i}$	=	N ₂ O emission factor for flaring in AB township or SK production class <i>i</i> (g/m ³)
ER_{N_2O}	=	flaring emission rate for N ₂ O (g/MJ) = 0.0000952 g/MJ (WCI.363(k) 2012)
HHV_i	=	higher heating value for township <i>i</i> (MJ/m ³)

Equation A3.2-11

$$Emis_{ij} = y_{ij} \times Vol_i \times \rho_j$$

$Emis_{ij}$	=	vented emissions of component <i>j</i> in AB township or SK production class <i>i</i> (kt)
y_{ij}	=	mole fraction of component <i>j</i> in AB township or SK production class <i>i</i>
Vol_i	=	volume of gas vented in AB township or SK production class <i>i</i> (10 ³ m ³)
ρ_j	=	density of component <i>j</i> at standard conditions (101.325 kPa and 15°C) (kg/m ³)

A3.2.2.1.3. Pneumatics, Compressor Seals and Fugitive Equipment Leaks

Methodology

The UOG Fugitive Emissions Model (FEM) estimates annual emissions from pneumatic devices (controllers and pumps), compressor seals and equipment leaks from 1990 onwards using a facility-based approach. The model utilizes the number of active UOG facilities and well sites along with average numbers of components per facility type (or asset ratios), component-level EFs, gas composition data and other source specific parameters to estimate emissions by province and industry segment for these sources.

The FEM is currently limited to the Western Canadian provinces of Alberta, Saskatchewan, British Columbia and Manitoba. In 2020, these provinces accounted for approximately 97% of total natural gas production and 93% of total crude oil production in Canada (Statistics Canada, n.d.[b], n.d.[d]).

The scope of the modelling work focusses on specific facility types including batteries, compressor stations and gas plants. The facilities are further broken down by subtype (e.g. single-well battery, multi-well group battery, etc.) and product type (e.g. light/medium crude oil, heavy crude oil, natural gas, etc.). All active well sites are also part of the FEM.

This approach facilitates continuous improvements via revisions to source data or model parameters, such as asset ratios or EFs for specific facility subtypes, product types or regions as new information becomes available. Given reliable data, changes to industry practices or government policy can also be reflected annually.

A summary of the FEM methodology is provided in the following sections. For complete documentation of the methodology including facility counts and modelling parameters, please refer to the *Upstream Oil and Gas Fugitive Emissions Model: Methodology and Documentation* (ECCC, 2021a).

FEM emission estimates for pneumatics, compressor seals and equipment leaks replace emissions for the same sources estimated using the methodology described in section A3.2.2.1.1 with some notable exceptions. Starting in 2020, Alberta pneumatics and compressor seal emissions are not included in final emission totals. Similarly, Saskatchewan estimates for pneumatics and compressor seals at all facilities, and fugitive equipment leaks at gas production and gas processing facilities are not included in final emission totals starting in 2020. In both cases this is due to revisions to provincial definitions of what operators are to include in reported vent gas volumes. As a result of these definition changes, estimates for these sources are not included in the final emission totals to avoid double counting. Please refer to section A3.2.2.1.5 for a more complete discussion of these changes.

Activity Data

Emission estimates in the FEM are built up from the annual number of active facilities and wells in British Columbia, Alberta, Saskatchewan and Manitoba. The FEM relies on several data sources, as described in Table A3.2–11, to determine the number of active facilities in the Western provinces. Where available, facility counts and well counts are derived directly from production accounting data (e.g. Petrinex, 2021; BCOGC, 2021b, MB ARD, 2021) or from data provided by provincial regulators (e.g. BCOGC, 2018). However, since complete production accounting data for each province back to 1990 is unavailable, it is necessary to estimate facility counts for years without data using other methods and data sources. For a complete description of how the available data sources are combined to provide the numbers of UOG facilities in these provinces from 1990 onwards and a listing of facility counts used in the FEM, please refer to the FEM methodology document (ECCC, 2021a).

Emission Factors and Other Parameters

Asset ratios representing the average number of each type of pneumatic device, compressor and equipment component per facility subtype are determined from the studies presented in Table A3.2–12. Other parameters such as the proportion of pneumatics powered by gas per facility subtype are also derived from these studies. For a complete listing of all asset ratios used in the FEM, please refer to ECCC (2021a).

Emissions from pneumatic devices are estimated using Equation A3.2–12 and the EFs presented in Table A3.2–13.

Alberta Environment and Parks maintains a registry of pneumatic device conversions that have taken place since 2012. This registry includes conversions from gas driven pneumatic pumps and controllers to electric and compressed air pneumatics (i.e. non-emitting devices), from high-bleed to low-bleed devices, and to vent gas capture systems. Similarly, the British Columbia Clean Infrastructure Royalty Credit Program and the CleanBC Industry Fund log pneumatic device conversions within British Columbia.

Data from these programs is used to reduce pneumatic device emission estimates in Alberta and B.C. to reflect the impact of these emission reduction activities. This reduction occurs from 2018 onwards as the field studies used to derive asset ratios occurred in the 2017/2018 time period and are expected to capture device conversions that occurred prior to the field studies.

Equation A3.2–12

$$Emis_{i,j,k,l,m} = \frac{FC_{j,k} \times PPF_{j,k,l} \times GDprop_{j,k} \times EF_{l,m} \times \rho \times x_i \times 8760}{10^6}$$

$Emis_{i,j,k,l,m}$	=	Emissions for gas species i , facility type j , product type k , pneumatic device l and scenario m (kt)
$FC_{j,k}$	=	Facility count for facility type j and product type k
$PPF_{j,k,l}$	=	Average number of pneumatic devices l , per facility type j and product type k
$GDprop_{j,k}$	=	Proportion of gas driven pneumatic devices per facility type j and product type k
$EF_{l,m}$	=	Emission factor for pneumatic device type l and pneumatic scenario m (m^3/hr)
ρ	=	density of released gas (kg/m^3)
x_i	=	mass fraction of species i
8760	=	number of hours per calendar year (24 h/d \times 365 d/yr)
10^6	=	kg per kt

Table A3.2-11 Data Sources Used to Determine Facility and Well Counts

Province	Years	FEM Facility Types	Data Source	Source Description
AB	2014–2020	All except Compressor Stations (CS) and Satellite Batteries (SatBat)	Petrinex (2021)	Petrinex monthly volumetric data
	2010–2013	All except Compressor Stations and Satellite Batteries	Alberta Energy Regulator (AER)	Petrinex annual volumetric data (preprocessed and provided by AER)
	2000–2009	All except CS, Gas Plants (GP) and SatBat	AER	Annual data provided by AER
	1990–2009	GP	AER (2020b)	AER ST50A: Gas Processing Plants in Alberta
	2000–2016	CS	IHS Markit (2018)	Counts derived by ECCC using IHS Markit (2018) data
	1990–2009	Well Sites	CAPP (2021)	Number of operating oil and gas wells (Tables 3.17 and 3.18)
BC	2010–2017	All except GP	BCOGC (2018)	BCOGC derived facility counts and production volumes
	2019–2020	All	BCOGC (2021b)	Petrinex monthly volumetric data
	2004–2018	GP	British Columbia Government (2020)	BC Gas Plant Report
	1990–2009, 2018	Well Sites	CAPP (2021)	Number of operating oil and gas wells (Tables 3.17 and 3.18)
SK	2000–2016	All except GP and SatBat	IHS Markit (2018)	IHS upstream oil and gas volumetric production accounting data
	2013–2020	GP	SK MER (2020e)	SK Gas Plant Reports
	1990–2020	Well Sites	CAPP (2021)	Number of operating oil and gas wells (Tables 3.17 and 3.18)
MB	1990–2020	Well Sites	MB ARD (2021)	Production reports by well

Table A3.2-12 Upstream Oil and Gas Fugitive Emissions Model Asset Ratio Data Sources

Emission Source	Province	Author	Year Completed	Title of Report
Pneumatics	All	Greenpath Energy Ltd.	2016	Modelling Inputs for Upstream Oil and Gas Methane Emission Sources
	AB, MB	Clearstone Engineering Ltd. and Carleton University	2018	Update of Equipment, Component and Fugitive Emission Factors for Alberta Upstream Oil and Gas
	SK	Advisian Ltd.	2019	Oil and gas inventory information enhancement and economic analysis study: Field data gather and interpret report
	BC	Cap-Op Energy	2019	British Columbia Oil and Gas Methane Emissions Field Study
Equipment Leaks	All	Greenpath Energy Ltd.	2016	Modelling Inputs for Upstream Oil and Gas Methane Emission Sources
	AB, SK, MB	Clearstone Engineering Ltd. and Carleton University	2018	Update of Equipment, Component and Fugitive Emission Factors for Alberta Upstream Oil and Gas
	BC	Cap-Op Energy	2019	British Columbia Oil and Gas Methane Emissions Field Study
Compressor Seals	AB, SK, MB	Clearstone Engineering Ltd. and Carleton University	2018	Update of Equipment, Component and Fugitive Emission Factors for Alberta Upstream Oil and Gas
	BC	Cap-Op Energy	2019	British Columbia Oil and Gas Methane Emissions Field Study

Emissions from reciprocating and centrifugal compressor seals are estimated using Equation A3.2-13 and the emission factors presented in Table A3.2-14.

Equation A3.2-13

$$Emis_{j,k} = \frac{FC_{j,k} \times CPF_{j,k} \times SPC_{j,k} \times Util_{j,k} \times SRF_m \times EF_m \times \rho \times x_i \times 8760}{10^6}$$

$Emis_{i,j,k,l,m}$	=	Compressor seal emissions for gas species i , facility type j and product type k (kt)
$FC_{j,k}$	=	Facility count for facility type j and product type k
$CPF_{i,k}$	=	Average number of compressors per facility type j and product type k
$SPC_{j,k}$	=	Average number of seals per compressor by facility type j and product type k
$Util_{j,k}$	=	Compressor utilization rate per 24 hour period per facility type j and product type k
SRF_m	=	Fraction of facilities using seal replacement frequency m
EF_m	=	Compressor seal emission factor for seal replacement frequency m ($\text{m}^3/\text{hr/cylinder}$)
ρ	=	density of released gas (kg/m^3)
x_i	=	mass fraction of species i
8760	=	number of hours per calendar year (24 h/d \times 365 d/yr)
10^6	=	kg per kt

Lastly, the emissions from equipment leaks are calculated using Equation A3.2–14 and the EFs presented in Table A3.2–15. The EFs are broken down by the type of production (i.e. natural gas or crude oil), type of service for the component (i.e. components under pressurized process gas service or process liquid service), component type and by leak detection and repair (LDAR) frequency. The LDAR frequency is represented by the corresponding LDAR scenarios as presented in Table A3.2–16. The LDAR scenarios differentiate between the frequency of LDAR activities occurring at the various oil and gas facility subtypes over the course of the time series.

Prior to the release of the CAPP *Best Management Practices for the Management of Fugitive Emissions at Upstream Oil and Gas Facilities* (CAPP, 2007), the “No LDAR” EFs, which assume no formal LDAR activities, are applied to all facilities except gas processing plants, where “Industry Measure 1” EFs are applied, which assumes LDAR activities approximately every 2 years. Starting in 2007, the “No LDAR” EFs are phased out for other facilities and the “Industry Measure 1” EFs are phased in. Similarly, “Industry Measure 2” EFs are phased in starting in 2015 to reflect more frequent LDAR activities of approximately every 16 months. Note that for most facility subtypes, a small fraction have the “No LDAR” EFs applied in each year, which decreases each year starting in 2007. This fraction represents the facilities of that subtype that handle small amounts of fluids and are unlikely to have formal LDAR activities in place.

Finally, the “Policy” scenario EFs are used starting in 2020 to reflect the implementation of both federal (ECCC, 2018) and provincial regulations (AB, 2018; BC, 2021; SK, 2020) to reduce CH₄ emissions from oil and gas operations. The federal methane regulations apply to all provinces except Alberta, British Columbia and Saskatchewan. All three of these provinces have their own regulations which are expected to produce equivalent CH₄ emissions reductions as the federal rules.

The LDAR portion of the federal regulations require LDAR surveys at most facility subtypes three times per year or every four months. Therefore, the “Policy 3” EFs are applied to Manitoba starting in 2020. Similarly, the Saskatchewan regulations require LDAR surveys twice a year, or every 6 months, at gas production and processing facilities. Therefore, the “Policy 2”

Table A3.2–13 Pneumatic Device Emission Factors

Province(s)	Pneumatic Device Type	Release Rate (m ³ /hr)
AB, SK, MB	Intermittent	0.00314
	Level ^a	0.378
	Positioner	0.247
	Pressure	0.430
	Temperature	0.00543
	Transducer	0.420
	Methanol Pump	0.636
	Other Chemical Pump	0.550
BC	Intermittent	0.00314
	Level	0.101
	Positioner	0.458
	Pressure	0.377
	Temperature	0.00543
	Transducer	0.453
	Methanol Pump	0.553
	Other Chemical Pump	0.250

Notes:
Unless otherwise indicated, emission factors were derived internally by the Oil, Gas and Alternative Energy Division (OGAED) at ECCC using Prasino (2013), Cap-Op (2019), Clearstone (2018) and Spartan Controls (2018).

a. Clearstone (2019)

Table A3.2–14 Compressor Seal Emission Factors

FEM Compressor Type	Seal Replacement Frequency Scenario	Emission Factor (m ³ /hr) ^a
Reciprocating	30 month	0.65
Reciprocating	60 month	1.17
Centrifugal – Wet Seal	NA	14.25
Centrifugal – Dry Seal	NA	6.34

Note:
Reciprocating emission factors are per compressor seal, while centrifugal EFs are per compressor.

a. Emission factors adapted from Carbon Limits (2017) for reciprocating compressors, and from API (2017) for centrifugal compressors.

EFs are applied to Saskatchewan starting in 2020. In the Alberta regulations, LDAR surveys are required annually at all facilities except gas plants and compressor stations, where a frequency of three times per year is required, meaning that “Policy 1” EFs are used at all facilities except gas plants and compressor stations where the “Policy 3” EFs are used. Lastly, the British Columbia regulations require LDAR surveys three times per year at most facilities and one time per year at smaller facilities.

Please refer to the FEM methodology document (ECCC, 2021a) for a complete listing of the proportions of each LDAR scenario that are applied to each facility subtype in each year and region.

Table A3.2–15 Fugitive Equipment Leak Emission Factors

Production Type	Service Type	Component Type	LDAR Scenario Emission Factor (g THC/hr) ^a					
			No LDAR ^b	Industry Measure 1 ^c	Industry Measure 2 ^c	Policy 1 ^c	Policy 2 ^c	Policy 3 ^c
Natural Gas	Process gas	Connector	0.820	0.635	0.567	0.513	0.267	0.185
		Valve	2.810	1.042	0.690	0.603	0.314	0.218
		OEL	467.000	120.210	75.960	66.249	35.764	25.082
		PRV	17.000	2.400	1.485	1.287	0.671	0.465
		Control Valve	16.200	4.604	2.830	2.452	1.285	0.892
		Meter	3.270	2.614	1.758	1.535	0.806	0.560
		Pump Seal	23.200	3.862	2.405	2.086	1.099	0.765
		Regulator	8.110	1.650	1.173	1.033	0.539	0.374
	Process liquid	Connector	0.550	0.111	0.106	0.098	0.051	0.035
		Valve	3.520	0.651	0.640	0.583	0.304	0.211
		OEL ^d	467.000	120.210	75.960	66.249	35.764	25.082
		PRV ^d	17.000	2.400	1.485	1.287	0.671	0.465
		Control Valve ^d	16.200	4.604	2.830	2.452	1.285	0.892
		Meter ^d	3.270	2.614	1.758	1.535	0.806	0.560
		Pump Seal ^d	23.200	3.862	2.405	2.086	1.099	0.765
		Regulator ^d	8.110	1.650	1.173	1.033	0.539	0.374
Crude Oil	Process gas	Connector	2.460	0.443	0.334	0.297	0.155	0.107
		Valve	1.510	0.199	0.143	0.126	0.066	0.045
		OEL	308.000	16.874	10.696	9.294	4.877	3.387
		PRV	16.300	11.318	6.797	5.872	3.065	2.125
		Control Valve	14.600	11.842	7.305	6.347	3.381	2.360
		Meter	1.300	1.042	0.810	0.720	0.375	0.260
		Pump Seal	35.880	28.702	17.514	15.184	8.028	5.590
		Regulator	6.680	1.880	1.309	1.150	0.600	0.416
	Process liquid	Connector	0.190	0.110	0.106	0.096	0.050	0.035
		Valve	1.210	0.688	0.590	0.531	0.276	0.192
		OEL ^d	308.000	16.874	10.696	9.294	4.877	3.387
		PRV ^d	16.300	11.318	6.797	5.872	3.065	2.125
		Control Valve ^d	14.600	11.842	7.305	6.347	3.381	2.360
		Meter ^d	1.300	1.042	0.810	0.720	0.375	0.260
		Pump Seal ^d	35.880	28.702	17.514	15.184	8.028	5.590
		Regulator ^d	6.680	1.880	1.309	1.150	0.600	0.416

Notes:

PRV = Pressure Relief Valve

OEL = Open Ended Line

a. THC = total hydrocarbons

b. CAPP (2005a)

c. Developed internally by the Oil, Gas and Alternative Energy Division (OGAED) at ECCC utilizing data or information from CAPP (2005a), CAPP (2014), Clearstone (2018, 2019) and Cap-Op (2019)

d. Assumed same emission factor as equivalent component in process gas service

	$Emis_{i,j,k,l,m} = \frac{FC_{j,k} \times CPF_{i,k,l} \times LDAR_{j,k,m} \times EF_{l,m} \times x_i \times 8760}{THC_k \times 10^9}$
$Emis_{i,j,k,l,m}$	Emissions for gas species i , facility type j , product type k , component l and LDAR scenario m (kt)
$FC_{j,k}$	Facility count for facility type j and product type k
$CPF_{i,k,l}$	Number of components l , per facility type j and product type k
$LDAR_{j,k,m}$	LDAR proportion per facility type j , product type k and LDAR scenario m
$EF_{l,m}$	Emission factor for component l and LDAR scenario m (g THC/hr)
x_i	mass fraction of species i
THC_k	Mass fraction of Total Hydrocarbons per product type k (g THC/g total gas)
8760	number of hours per calendar year (24 h/d × 365 d/yr)
10⁹	g per kt

The FEM also uses gas composition data from the EERL study (see A3.2.2.1.2) to determine the CO₂ and CH₄ emissions resulting from pneumatic devices, compressor seals and equipment leaks. For the years 2010–2020, where detailed production accounting data for Alberta is available, the township-level Alberta gas composition data is used in conjunction with township-level facility counts to estimate emissions. As detailed production accounting data required to determine facility counts by Alberta township is not available for 1990–2009, average gas compositions, derived from the EERL study data and presented in Table A3.2–17 are used.

Table A3.2–16 Frequency of LDAR Activities by LDAR Scenario

LDAR Scenario	LDAR Frequency (months)
No LDAR	no formal LDAR program
Industry Measure 1	24
Industry Measure 2	16
Policy 1	12
Policy 2	6
Policy 3	4

Table A3.2–17 Average Natural Gas Compositions used in the Upstream Oil and Gas Fugitive Emissions Model

Province	FEM Product Type	CH ₄	CO ₂	H ₂ S	C ₂ H ₆	VOC	Density (kg/m ³)
		Mass Percent					
AB	All Gas Types	73.32	2.86	1.25	10.00	10.48	0.8016
	CHOPS	91.56	2.12	0.00	1.66	0.90	0.7096
	Gas Processing	72.25	2.88	0.14	11.14	11.89	0.8089
	Heavy Oil	89.44	6.62	0.02	1.06	1.60	0.7252
	Light/Med Oil	67.33	2.53	0.69	11.01	15.67	0.8393
BC	All Gas Types	71.44	2.84	0.54	11.56	12.21	0.8130
	Gas Processing	71.10	2.81	0.58	11.55	12.52	0.8151
	Light/Med Oil	68.33	2.58	0.94	11.49	15.01	0.8331
MB	All Gas Types	90.20	0.89	0.00	1.17	1.97	0.7133
	Gas Processing	89.58	1.09	0.01	1.61	2.58	0.7172
	Light/Med Oil	78.89	0.97	0.01	4.24	10.97	0.7745
SK	All Gas Types	90.20	0.89	0.00	1.17	1.97	0.7133
	CHOPS	93.35	0.84	0.01	1.30	0.59	0.7009
	Gas Processing	89.58	1.09	0.01	1.61	2.58	0.7172
	Heavy Oil	94.53	0.47	0.00	1.22	0.62	0.6967
	Light/Med Oil	78.89	0.97	0.01	4.24	10.97	0.7745

Note:

CHOPS = Cold Heavy Oil Production with Sand

The detailed analysis of gas composition data completed for Alberta in the EERL study has not taken place for the provinces of British Columbia, Saskatchewan and Manitoba. Oil and gas formations (as shown in Figure A3.2–3) that span the British Columbia–Alberta and Saskatchewan–Alberta borders were used to estimate gas compositions for these neighbouring provinces. As a similar method is not possible for Manitoba, the Saskatchewan gas compositions are applied. All average gas compositions used in the FEM are summarized in Table A3.2–17.

Average gas compositions by Saskatchewan production classes (SK MER, 2021b) are available but ECCC does not currently have facility counts broken down by production class. Once available, the Saskatchewan gas compositions will be incorporated into the FEM.

For a full description of the methodology, data sources, EFs and parameters used in the FEM please refer to the FEM methodology document (ECCC, 2021a).

A3.2.2.1.4. Surface Casing Vent Flows

Methodology

Surface casing vent flow (SCVF) emissions for the provinces of Alberta and British Columbia are estimated directly instead of extrapolated from the CAPP and UOG studies (CAPP, 2005a; EC, 2014) as outlined in section A3.2.2.1.1. Both provinces have regulatory measures (EUB, 2003; BC, 2021) that dictate how operators detect, report, and resolve SCVFs at wells within their provincial boundaries. The reported data collected by Alberta and British Columbia (AER, 2021d; BCOGC, 2021c) is used to better represent the variability of this source by location and industry subsector.

The methodology described in section A3.2.2.1.1 is applied in all other provinces and territories where onshore oil and gas extraction occurs.

Activity Data

Reported SCVF data collected by Alberta and British Columbia is publicly available (AER, 2021d; BCOGC, 2021c). The information contained in these reports is used to estimate annual SCVF emissions directly. Although the regulations for SCVF repair came into force in 2003 in Alberta and 2010 in British Columbia, records of detected vent flows exist in the provincial databases prior to 1990 for Alberta and 1993 for B.C. This enables estimates to be prepared for the entire time series, when other relevant well information is included (AER, 2021e; BCOGC 2021d, 2021e).

Under both Alberta and British Columbia regulations, the deadline to resolve detected SCVFs depends on whether they are classified as “serious” or “non-serious”. The definition of a serious SCVF is the same in both provinces, and applies if any of the criteria in Table A3.2–18 are observed at a well. Table A3.2–18 summarizes other components of the provincial requirements used in estimating emissions.

Table A3.2–18 Provincial Requirements for Surface Casing Vent Flow Testing, Reporting, and Repair

Regulatory Component	Alberta	British Columbia
Regulation Name	Interim Directive ID 2003-01	B.C. Reg. 282/2010 – Drilling and Production Regulation
Testing Requirements	<ul style="list-style-type: none"> • Within 90 days of drilling rig release • Annually for five years after detection 	<ul style="list-style-type: none"> • At rig release, or immediately after any completion • As part of lifetime routine maintenance • Before suspension, abandonment, or permit transfer
Serious SCVF Definition	<p>Serious SCVFs meet one or more of these criteria:</p> <ul style="list-style-type: none"> • Hydrogen sulfide (H_2S) is present • Gas flowrate is greater than or equal to 300 cubic metres per day (m^3/d) • Stabilized shut-in pressure is greater than one half the formation leak-off pressure at the surface casing shoe or 11 kPa/m times the surface casing setting depth • Hydrocarbon liquid (oil) vent flow is present • Vent flow occurred due to wellhead seal failures or casing failure • Water vent flow is present, if the water contains substances that could cause soil or groundwater contamination • Any usable water zone is not covered by cemented casing • Vent flow constitutes a fire, public safety, or environmental hazard 	
Reporting Requirements	<ul style="list-style-type: none"> • Within 30 days of detection • Annual test results are not reported 	Serious: Immediately after discovery Non-Serious: Within 30 days of discovery <ul style="list-style-type: none"> • Regular test results are reported
Repair Requirements	Serious: 90 days from discovery Non-Serious: prior to well abandonment	Serious: “Immediately” after discovery Non-Serious: prior to well abandonment

Table A3.2-19 Key Information Extracted from Surface Casing Vent Flow Data Sources

Province	Name of Data Source	Key Information
AB	AER Vent Flow and Gas Migration Report	Report Date, Resolution Date, Reported Resolution, Classification (Serious or Non-Serious)
	Well Infrastructure Report (from Petrinex)	Finished Drill Date, Well Status (active, abandoned, etc.), Well Status Date
BC	BCOGC BIL 185 – Surface Casing Vent Flow	Test Date, Classification (Serious or Non-Serious), Well Mode Code (active, abandoned, etc.)
	BCOGC Well Index Report (BCOGC-2555)	Rig Release Date, Last Production Date
	BCOGC Well Surface Abandonment Report (BCOGC-41437)	Abandonment Date (if applicable)

A
3**Table A3.2-20 Assumptions Based On Regulatory Requirements For Different Surface Casing Vent Flow Reporting Scenarios**

Province	Scenario	Assumptions by Surface Casing Vent Flow Classification	
		Serious	Non-Serious
AB	Report Date before Resolution Date	SCVF starts 90 days before Report Date; ends at Resolution Date	SCVF starts at Finished Drill Date; ends at Resolution Date OR Abandonment OR continues to present (if leak is not resolved or well is not abandoned)
	Report Date equals Resolution Date		
	Report Date after Resolution Date	SCVF starts 90 days before Resolution Date	SCVF starts at Finished Drill Date
	No resolution reported	SCVF ends 90 days after Report Date	SCVF continues to present
BC	Test Date before Rig Release Date	SCVF starts at Test Date; ends at Repair Date	SCVF starts at Rig Release Date; ends at Abandonment Date OR Repair Date OR continues to present
	Well Mode is Abandoned at Test Date	SCVF starts at Abandonment Date; ends at Repair Date	
	Other	SCVF starts at Rig Release Date; ends at Repair Date	

Note:

For British Columbia, Repair Date is any subsequently reported Test Date where gas flowrate is zero. If no subsequent test is reported, Repair Date is based on B.C. Reg. 282/2010 requirements.

An important aspect of the method is to determine when a SCVF occurred and its duration, which requires several pieces of reported information. For Alberta, the duration is based on the records in the *Well Vent Flow/Gas Migration Report* (AER, 2021d), as well as the *Well Infrastructure Report* from the Petrinex reporting system (AER, 2021e). A similar process is used for British Columbia, where reports of wells with SCVF are linked to the *Well Index and Well Surface Abandonment* databases made available by the BCOGC (2021d, 2021e). Table A3.2-19 highlights the required information from each data source.

When these key dates are known for a reported vent flow, along with the well status and reported resolution, the leak duration is estimated directly. Interpretation of the report dates, resolution dates, and well status dates in the records requires assumptions based on the regulatory requirements in each province, as they are currently the best available source of information on SCVF mitigation practices. These simplifying assumptions are stated in Table A3.2-20.

Emission Factors

Reported surface casing vent flowrates are applied for the estimated duration associated with each record in the provincial databases. While AER data contains one record for each occurrence, BCOGC data contains records of follow up tests on wells with SCVF, meaning emission rates for each source reflect any reported changes over time, whether due to an attempted repair or natural fluctuations in the vent flow. For records where SCVF is reported without a gas flow rate, the average flow rate is applied based on the location (AER sub-region in Alberta; provincially in British Columbia) and reported severity (serious or non-serious).

Geographic information is also considered, as the composition of the natural gas emitted depends on the location of the source. Gas compositions from Tyner and Johnson (2020) are assigned to the reported surface casing vent flowrate in the same manner as described for the fugitive sources in section A3.2.2.1.3. Township-specific compositions are applied in Alberta, and compositions from representative locations are used to estimate the average gas composition from wells in British Columbia. While the natural gas in vent flows may originate from formations other than those being produced by the well, the Tyner and Johnson (2020) gas composition data remains the most comprehensive location specific information presently available to ECCC. Should more representative speciation data for SCVFs in Canada become available, the methodology is designed such that it could be readily adopted.

Emissions from SCVFs are allocated to the correct oil and gas production subsector using detailed well information from AER (2021e) and BCOGC (2021d) databases. As with key dates, provincial vent flow databases are linked to these data sources to extract the necessary well categorizations. Depending on the information available, either the associated facility

subtype, production type, or production fluid density is used to allocate SCVF emissions from each well to the appropriate industry subsector, such as natural gas production, light/medium crude oil production, heavy crude oil cold production and heavy crude oil thermal production.

Annual SCVF emissions of CH_4 and CO_2 from individual wells are calculated directly using Equation A3.2–15:

Equation A3.2–15

$$\text{Emis}_{i,w} = y_{i,t} \times \rho_{i,t} \times LR_w \times LD_w$$

$\text{Emis}_{i,w}$	=	SCVF emissions for component i and well w
$y_{i,t}$	=	mole fraction of component i and location t
$\rho_{i,t}$	=	density (kg/m^3) of component i and location t
LR_w	=	surface casing vent gas flowrate (m^3/day) from well w
LD_w	=	number of days per year where vent flow occurs at well w

A3.2.2.1.5. Changes to Alberta and Saskatchewan Vent Gas Definitions

Effective January 1, 2020, both Saskatchewan and Alberta changed the definitions of fuel gas, flare gas and vent gas in their respective measurement and reporting requirements. *Directive 017* (AER, 2020c) in Alberta now defines gas released from pneumatic instruments as vent gas, where it was previously defined as fuel gas, and gas released from compressor seals and glycol dehydrators to also be reported as vent gas. Similarly, Saskatchewan's *Directive PNG017* (SK MER, 2020) now requires gas released from pneumatic instruments, compressor seals and equipment leaks to be reported as vent gas.

Due to gaps in previous measurement and reporting requirements for reported venting, emissions from pneumatic instruments, compressor seals, glycol dehydrators, and equipment leaks were estimated and included separately for the years 1990 to 2019. However, because of these changes in reporting, separate emission estimates of pneumatics, compressor seals and glycol dehydrators are no longer required for 2020 and beyond in Alberta. Similarly, separate emission estimates for pneumatics, compressor seals and equipment leaks are no longer required for 2020 and beyond in Saskatchewan. This change is required to ensure no double-counting of emissions.

In Saskatchewan, the *Oil and Gas Emissions Management Regulations* (OGEMR) (SK, 2020) only require leak detection and repair (LDAR) at gas production and processing facilities. *Guideline PNG035: Estimating Venting and Fugitive Emissions* (SK MER, 2019) provides guidance to operators on how to quantify gas released from equipment leaks which are identified during LDAR activities. Since LDAR is only required at gas facilities, it is assumed that reported vent volumes include equipment leak emissions at gas facilities in Saskatchewan. However, since LDAR is not required at oil production facilities, it is assumed that equipment leaks are not identified, quantified or reported as vent gas at these facilities. Therefore, equipment leaks at gas facilities in Saskatchewan are not estimated separately while equipment leaks at oil facilities are estimated separately and included in the emission totals.

These changes in Saskatchewan and Alberta reporting also introduce a methodological inconsistency starting in 2020. At present, ECCC does not possess reported vent data with sufficient resolution to, for example, compare the vented emissions from pneumatic instruments estimated by ECCC with those reported by operators to Petrinex. Analyzing data at this level of detail would help in assessing the relative contribution of the inconsistent methodologies to the overall decrease in emissions between 2019 and 2020. This issue is further complicated by the oil and gas emissions regulations that came into effect January 1, 2020 in Saskatchewan and Alberta.⁷ Due to the regulations, a reduction in emissions is expected. This issue is a priority for ECCC and is being actively investigated.

⁷ Under the Canadian Environmental Protection Act, 1999 (CEPA), the *Regulations Respecting Reduction in the Release of Methane and Certain Volatile Organic Compounds (Upstream Oil and Gas Sector)*, SOR/2018-66 (the “federal methane regulations”) were published in the Canada Gazette, Part II, vol. 152, no. 1 on April 26, 2018. The federal methane regulations came into force on January 1, 2020, except sections 26, 27 and 37 to 41, which come into force on January 1, 2023. Section 10 of CEPA authorizes the Minister of the Environment to enter into an equivalency agreement with a province, territory or aboriginal government if the provisions within that jurisdiction are equivalent to a regulation made under CEPA.

Equivalency agreements were established for the federal methane regulations with Alberta (ECCC, 2020a), British Columbia (ECCC, 2020b), and Saskatchewan (ECCC, 2020c).

A3.2.2.2. Natural Gas Transmission and Storage

Methodology

Virtually all of the natural gas produced in Canada is transported from the processing plants to the gate of the local distribution systems by high-pressure pipelines. The majority of emissions are from equipment leaks and process vents along these pipelines.

Fugitive emissions for natural gas transmission are based on several documents. The first, *CH₄ and VOC Emissions from the Canadian Upstream Oil and Gas Industry* (CAPP, 1999), was prepared by Clearstone Engineering Ltd. for CAPP in July 1999. The second source is ancillary tables provided by Clearstone Engineering Ltd. that describe the CO₂ emissions. There are no N₂O fugitive emissions from natural gas transmission. The CO₂ and CH₄ emissions for 1990–1996 are taken directly from the two sources. The CO₂ and CH₄ emissions for 1997–1999 were estimated based on province/territory natural gas transmission pipeline length and leakage rates, which were developed based on the 1996 emissions from CAPP (1999) and pipeline lengths from Statistics Canada.

For the years 2005 and 2011, emissions are taken from the UOG study (EC, 2014), which followed an IPCC Tier 3 approach that rolled-up the reported GHG emissions from individual natural gas companies. Input data for the natural gas transmission and storage industry was compiled by ORTECH Consulting Inc. (2013) for the Canadian Energy Partnership for Environmental Innovation (CEPEI). Data for the years 2000–2004, 2006–2010 and 2012–2014 was provided directly by CEPEI, again following an IPCC Tier 3 approach. Emission estimates for 2015–2020 were extrapolated from 2014 data using the same extrapolation method as described for the UOG sector (see Equation A3.2–5), with the length of natural gas transmission pipeline used as the activity factor.

The emissions are calculated per province/territory and then summed to obtain the total CO₂ and CH₄ emissions for Canada. Newfoundland and Labrador, Prince Edward Island, Yukon, and Nunavut do not have natural gas transmission pipelines. However, there are natural gas gathering lines in Yukon, and fugitive emissions from those lines are accounted for in the 1.B.2.b.2 – Natural Gas – Production category of the CRF table.

No natural gas transmission pipelines were operating in Nova Scotia, New Brunswick or the Northwest Territories until 1999.

Similar to natural gas transmission, fugitive emissions from natural gas storage are taken from the UOG study (EC, 2014) for the years 2005 and 2011. Data for the years 2000–2004, 2006–2010 and 2012–2014 was provided directly by CEPEI. Emission estimates for 1990–1999 and 2015–2020 were extrapolated using the previously described extrapolation methods, with the volume of gas delivered to and withdrawn from storage as the activity factor.

Activity Data

The activity data required to estimate the fugitive emissions from natural gas transmission for 1997–1999 and 2015–2020 is the annual length of the natural gas transmission pipeline by region. Transmission pipeline lengths were published annually by Statistics Canada in *Natural Gas Transportation and Distribution*. Statistics Canada has discontinued this publication but still collects the data and releases it to ECCC (Statistics Canada, 2021). However, pipeline length data was only available up to and including 2019; pipeline lengths for 2020 were therefore estimated. For Quebec, Ontario, Manitoba, Saskatchewan, Alberta, British Columbia and the Northwest Territories, the 2020 pipeline lengths were estimated based on the average annual change in length between 2000 and 2019. The 2020 values were assumed to be the same as 2019 for New Brunswick and Nova Scotia since the natural gas transmission pipeline lengths have not changed since 2003 and 2002, respectively. Improvements to the model are being investigated.

For natural gas storage, annual volumes of natural gas delivered to storage and withdrawn from storage are taken from *Canadian natural gas storage, Canada and provinces* (Statistics Canada, n.d.[f]) for the 2015–2020 time period and *Natural gas utilities, monthly receipts and disposition* (Statistics Canada, n.d.[g]) for data prior to 2015.

A3.2.2.3. Petroleum Refining

The refinery model is based on the study *Economic and Environmental Impacts of Removing Sulphur from Canadian Gasoline and Distillate Production* (CPPI, 2004), prepared for the Canadian Petroleum Products Institute (CPPI), Natural Resources Canada (NRCan), Environment Canada and Industry Canada in 2004 by Levelton Consultants Ltd. The study surveyed the refining industry and used this data, along with data collected by the Canadian Industrial Energy End-Use Data and Analysis Centre, to develop GHG emission estimates for 1990 and 1994–2002.

There are three sections in the refinery methodology: fugitive (unintentional releases), process venting and flaring. The combustion methodology for petroleum refining is discussed in Annex 3.1 of the National Inventory Report.

Methodology

Fugitive Emissions

The CO₂ and CH₄ emission factors were developed by Levelton Consultants Ltd. and were presented in the refinery study (CPPI, 2004). These EFs are used to estimate the fugitive emissions for the years not included in the study, i.e. 1991–1993 and 2003 onwards.

The fugitive emissions are generated using Equation A3.2–16.

Equation A3.2–16

$$\text{FugitiveGHGEmissions}(t) = \text{EmissionFactor}(t/\text{GJ}) \times \text{RefineryAnnualEnergyConsumption}(\text{GJ})$$

The refinery annual energy consumption (in GJ) is the sum of the energy of all fuels consumed by refineries in the *Report on Energy Supply and Demand in Canada* (Statistics Canada, 1990–), including fuels listed under producer consumption from the refined petroleum products table. The energy consumption value is the same as that in the stationary combustion model for 1.A.1.b Petroleum Refining of the CRF table.

The EFs are 2.78 t CO₂/GJ for CO₂ and 11.89 t CH₄/GJ for CH₄.

The refinery study has listed fugitive N₂O emissions for 1990 and 1994–2002 as a constant 100 t N₂O/year; however, there were not enough data to develop an emission factor for them. The N₂O emissions were kept constant at 100 t N₂O/year for the years 1991–1993 and 2003 onwards. It is assumed that the reported N₂O emissions from the refinery study are a residual from combustion sources and that the majority of N₂O emissions associated with petroleum refining are correctly reported in the stationary combustion section of the inventory.

Process Emissions (Venting)

Process emissions are mainly associated with the venting of CO₂ from the production of hydrogen using natural gas. This hydrogen is used as an input in the production of refined petroleum products (RPPs). Using data provided from the refinery study for the years 1990, 1994–1998 and 2000–2002, CO₂ emissions from the production of hydrogen were correlated to refinery annual RPP production. These results were used to estimate CO₂ emissions for the years 1991–1993, 1999 and 2003 onwards.

Flaring Emissions

Flaring emissions have been determined for CO₂, CH₄ and N₂O using the estimates from the refinery study and RPP production by Canadian refineries. The study provided emissions for the years 1990, 1994–1998 and 2000–2002, and these emissions were correlated to refinery annual RPP production. Flaring emissions for the years 1991–1993, 1999 and 2003 onwards were estimated based on this correlation and known RPP production data.

Activity Data

The activity data required to estimate the fugitive emissions from refineries is listed in Table A3.2–21.

Table A3.2–21 Required Refinery Activity Data and Their Sources

Publisher	Publication	Activity Data
Statistics Canada	<i>Report on Energy Supply and Demand in Canada</i> (RESD) (Statistics Canada, 1990–)	Refinery and producer consumption (by refineries) annual energy consumption. Refinery RPP production
Canadian Petroleum Products Institute (CPPI)	<i>Economic and Environmental Impacts of Removing Sulphur from Canadian Gasoline and Distillate Production</i> by Levelton Consultants Ltd. (CPPI, 2004)	Fugitive Emissions Table 3–2 CPPI Regional GHG Inventory—Detailed (kilotonnes) Process Emissions Table 3–2 CPPI Regional GHG Inventory—Detailed (kilotonnes) Flaring Emissions Appendix E—Flare Gas

A3.2.2.4. Natural Gas Distribution

Methodology

Fugitive emissions for the 1990–1999 time period from natural gas distribution are based on the Canadian Gas Association (CGA) report titled *1995 Air Inventory of the Canadian Natural Gas Industry* (CGA, 1997) and the Gas Research Institute (GRI) report titled *Vented Emissions from Maintenance at Natural Gas Distribution Stations in Canada* (GRI, 2000). The CGA study estimated emissions from the Canadian gas pipeline industry for the years 1990 and 1995 using an IPCC Tier 3 approach. Emissions were calculated based on EFs from the U.S. EPA, other published sources and engineering estimates. The activity data was obtained from published sources and specialized surveys of gas distribution system companies. The surveys contained information on equipment schedules, operating parameters of equipment, pipeline lengths used in the Canadian distribution system, etc. The GRI (2000) report is an update to the CGA (1997) study with more accurate and better substantiated data for station vents. An emission factor was developed for the distribution system based on the study data (CGA, 1997; GRI, 2000) and on gas distribution pipeline distances by province provided by Statistics Canada, which were then used to estimate emissions for the 1990–1999 time period.

For 2000 and onwards, emissions are based on data from the UOG study (EC, 2014), following an IPCC Tier 3 approach that rolled up the reported GHG emissions from individual natural gas companies for 2005 and 2011. Input data for the natural gas distribution industry was compiled by ORTECH Consulting Inc. (2013) for CEPEI. Data for the years 2000–2004, 2006–2010 and 2012–2014 was provided directly by CEPEI, again following an IPCC Tier 3 approach. Emission estimates for 2015–2020 were estimated using the length of natural gas distribution pipeline, taking the approach governed by Equation A3.2–5.

The fugitive emissions for natural gas distribution are estimated for each province and then summed to obtain the overall emissions for Canada. At present, no natural gas distribution pipelines exist in the following provinces and territories: Newfoundland and Labrador, Prince Edward Island, Nunavut, Yukon, and Nunavut.

Activity Data

The required activity data is the length of natural gas distribution pipeline per province, which was historically published in Statistics Canada's *Natural Gas Transportation and Distribution* report. Statistics Canada discontinued this publication in 2003 but still collects the data and releases it to ECCC (Statistics Canada, 2021). However, pipeline length data was only available up to and including 2019; pipeline lengths for 2020 were therefore estimated for all provinces based on the change in length between 2018 and 2019.

For New Brunswick and Nova Scotia, pipeline lengths for 2000–2006 were provided by Enbridge Gas New Brunswick⁸ and Heritage Gas,⁹ respectively. In the Northwest Territories, the Ikhil Pipeline began providing Inuvik with natural gas in 1999. Distribution lengths for 1999–2006 were backcast based on the change in distribution length between 2007 and 2008.

The 2007 pipeline length for British Columbia provided by Statistics Canada was twice the 2006 value. Statistics Canada confirmed that the data for 2006 and previous years was incorrect but was unable to provide corrected distribution lengths. It was assumed that the 1999 value was correct, and a linear trend was used to fill in the 2000–2006 data.

A3.2.2.5. Oil Sands and Heavy Oil Upgrading Industry

The oil sands and heavy oil upgrading (OS/HOU) industry produces synthetic crude oil and other products from bitumen. Bitumen is a naturally occurring viscous mixture consisting of hydrocarbons heavier than pentane and other contaminants (e.g. sulphur compounds); in its natural state, it will not flow under reservoir conditions or on the surface. Bitumen occupies the lower end of the range of heavy crude oils and is sometimes referred to as ultra-heavy crude oil. “Oil sands” is a term applied by the Government of Alberta to a particular geographical area of the province of Alberta that contains concentrations of bituminous sands as well as deposits of other heavy crude oil. Bituminous sands are an unconsolidated mixture of sand, clay, water and bitumen.

In this area, bitumen is extracted from open-pit mined oil sands or from in situ bitumen operations using thermal extraction techniques. The emissions from in-situ bitumen extraction are included in the UOG study (CAPP, 2005a). Fugitive emissions from the mining, processing and upgrading of bitumen and heavy oil are taken from two separate reports: *An Inventory of GHGs, CACs, and H₂S Emissions by the Canadian Bitumen Industry: 1990 to 2003* (CAPP, 2006), prepared by Clearstone

⁸ Enbridge Gas New Brunswick. 2010. Personal communication (email from Nicholson L, Communications Coordinator, Enbridge Gas New Brunswick, to Smyth S, Pollutant Inventories and Reporting Division, Environment Canada, dated December 7, 2010).

⁹ Heritage Gas. 2010. Personal communication (email from Bracken J, President, Heritage Gas to Smyth S, Pollutant Inventories and Reporting Division, Environment Canada, dated December 7, 2010).

Engineering Ltd. for CAPP (referred to hereafter as the bitumen study), and an update to the study that was completed in 2017 by Clearstone for ECCC titled *An Inventory of GHGs, CACs, and Other Priority Emissions by the Canadian Oil Sands Industry: 2003 to 2015* (ECCC, 2017) (referred to hereafter as the oil sands study).

In general, the bitumen study (CAPP, 2006) is the basis for the 1990–2003 fugitive emissions estimates, and the oil sands study (ECCC, 2017) is the basis for the 2004–2020 fugitive emission estimates for the OS/HOU industry. The major emission sources in the OS/HOU industry are the following:

- process emissions from the steam reforming of natural gas to produce hydrogen for upgraders
- CH₄ present in the oil sands deposits that is released during mining, mine dewatering and ore handling activities
- volatilization of hydrocarbons from the exposed oil sands and during transport and handling of the oil sands
- biogenic gas formation (primarily CH₄) in tailings ponds
- volatilization and decomposition of residual bitumen and diluent, which carry through to the tailings ponds
- fugitive equipment leaks, venting, flaring and storage losses at ore preparation, extraction and upgrader plants and their associated utility and cogeneration plants
- spills and accidental releases
- secondary sources, such as sewage treatment facilities, landfills, onsite construction and fabrication activities, motor vehicle fleets, corporate aircraft, and boats and dredges used on the tailings ponds

Bitumen Study: 1990–2003 Emission Estimates

The bitumen study (CAPP, 2006) is a compilation of the individual Tier 3 inventories of facilities involved in the OS/HOU industry from 1990–2003. Table A3.2–22 lists the OS/HOU facilities included in the study.

The facility boundaries were determined to ensure that all target emissions, including those from cogeneration facilities, were included.

The bitumen study (CAPP, 2006) used emissions from individual facility reports, where available. These emissions were verified against inventories and data reported to Alberta Environment. When this was not possible, emissions were estimated on the basis of available activity data and emission factor data. There were two methods for estimating emissions. The first method—the emission factor method—uses specific activity data and standard EFs. If no activity data were available, the emission factor ratio technique was applied. Refer directly to the bitumen study (CAPP, 2006) for a discussion of the specific methodologies.

The following sources were used to estimate emissions:

- facility operator information
- energy statistics published by the Alberta Energy Regulator (AER)
- source emission monitoring results reported to Alberta Environment
- data from company submissions to the Voluntary Challenge Registry
- environmental impact assessment files as part of recent energy development applications in the OS/HOU industry
- open literature

Consult the bitumen study (CAPP, 2006) for more details.

Table A3.2–22 List of Oil Sands and Heavy Oil Upgrading Facilities in the Bitumen Study (CAPP, 2006)

Operator	Facility Name
Husky Energy Inc.	Lloydminster Upgrader
Consumer's Co-operative Refineries Ltd.	Regina Upgrader
Suncor Energy Inc.	Tar Island
Syn crude Canada Ltd.	Mildred Lake and Aurora

Oil Sands Study: 2003–2020 Emission Estimates

The oil sands study (ECCC, 2017) is a facility-based Tier 3 emissions inventory for the OS/HOU industry completed for the 2015 reference year. It was used as the basis for extrapolating emissions both forwards and backwards in time. Where facility emission reports were available from operators, extrapolation was not required and actual emissions were used. These emission records were verified by Clearstone Engineering Ltd. Table A3.2–23 is a list of the OS/HOU facilities included in the study.

The Regina Upgrader operated by Consumers' Co-operative Refineries Limited was excluded from the oil sands study because it is defined strictly as a refinery even though it does upgrade some heavy crude oil. The refinery began operation in 1935 and added upgrading capabilities in 1988. It was included in the bitumen study (CAPP, 2006) due to its capabilities to upgrade heavy crude oil. Fugitive emissions for this facility are estimated using the refinery model (see section A3.2.2.3).

In 2016, the Horizon liquid extraction plant operated by Inter Pipeline Offgas Ltd. came online. Emissions from this facility were estimated using emissions data from the Suncor liquid extraction plant (ECCC, 2017) and facility-level activity data (AER, 2021f) for the two facilities. This method is justified due to the similar operations at the two facilities. In late 2017, the Fort Hills mine started operations. Emission estimates for this facility were developed using emissions data reported to the GHG Reporting Program (GHGRP) (ECCC, 2021b).

Depending on when each facility commenced operation, emissions were estimated using data from either the bitumen study (CAPP, 2006), the oil sands study (ECCC, 2017), or both. Table A3.2–24 shows the study used to estimate emissions for each year of the time series for each facility.

Table A3.2–23 List of Oil Sands and Heavy Oil Upgrading Facilities in the ECCC Bitumen Study (ECCC, 2017)

Operator	Facility Name	Oil Sands Operations
Suncor Energy Inc.	Millennium & Steepbank Mines and Upgrader	Integrated Mining and Upgrading
Syn crude Canada Ltd.	Mildred Lake & Aurora Mines and Upgrader	
Canadian Natural Resources Ltd.	Horizon Mine and Upgrader	
Husky Energy Inc.	Lloydminster Upgrader	Upgrading
Shell Canada Energy	Scotford Upgrader	
Nexen Energy ULC	Long Lake Upgrader	
Imperial Oil Resources	Kearl Mine	Mining and Ore Processing
Canadian Natural Upgrading Ltd.	Muskeg River and Jackpine Mines	
Aux Sable Canada Ltd.	Heartland Offgas Plant	Hydrocarbon Liquids Extraction
Inter Pipeline Offgas Ltd.	Suncor Liquids Extraction Plant	

Table A3.2–24 Basis of Emission Estimates for Each Facility in the Oil Sands and Heavy Oil Upgrading Industry

Operator	Facility Name	Bitumen Study	Oil Sands Study
Suncor Energy Inc.	Millennium & Steepbank Mines and Upgrader	1990–2003	2004–2020
Syn crude Canada Ltd.	Mildred Lake & Aurora Mines and Upgrader	1990–2003	2004–2020
Husky Energy Inc.	Lloydminster Upgrader	1992–2003	2004–2020
Canadian Natural Upgrading Ltd.	Muskeg River and Jackpine Mines	-	2002–2020
Shell Canada Energy	Scotford Upgrader	-	2003–2020
Inter Pipeline Offgas Ltd.	Suncor Liquid Extraction Plant	-	2003–2020
Canadian Natural Resources Ltd.	Horizon Mine and Upgrader	-	2008–2020
Nexen Energy ULC	Long Lake Upgrader	-	2009–2020
Aux Sable Canada Ltd.	Heartland Offgas Plant	-	2011–2020
Imperial Oil Resources	Kearl Mine	-	2013–2020
Inter Pipeline Offgas Ltd.	Horizon Liquid Extraction Plant	Emission estimates for 2016–2020 were developed using emissions data for the Suncor Liquid Extraction Plant (ECCC, 2017) and facility level activity data (AER, 2021f).	
Fort Hills Energy Corporation	Fort Hills Mine	Emission estimates for 2017–2020 were developed from data reported to the Greenhouse Gas Reporting Program (ECCC, 2021b).	

Table A3.2–25 Activity Data Required for the Oil Sands Model

Oil Sands Operation	Source Category	Subcategory	Activity Data for Extrapolation
Hydrocarbon Liquids Extraction	Flaring and Incineration	All	Process Gas Receipts (AER, 2021f)
	Fugitive	Equipment Leaks	
	Venting	All	
Mining and Ore Processing	Flaring and Incineration	All	Crude Bitumen Production (AER, 2021f)
	Fugitive	Equipment Leaks	
		Exposed Mine Face	
		Other	
		Storage Losses	
		Tailings Ponds	
	Process Emissions	Sulphur Recovery	
Upgrading	Venting	All	Synthetic Crude Oil Production (AER, 2021f; Husky Energy Inc., 1998–2019; Cenovus Energy, 2021)
	Flaring and Incineration	All	
	Fugitive	Equipment Leaks	
		Other	
		Spills and Pipeline Ruptures	
		Storage Losses	
	Venting	All	
Process Emissions		Sulphur Recovery	
		H ₂ Production	

Methodology for Extrapolating Emission Estimates

The oil sands model provides emission estimates for the OS/HOU industry for 2003–2020 by multiplying base year emissions data (i.e. 2015) by the ratio of the activity data for the non-inventoried year to that of the base year, as shown in Equation A3.2–17. The base year emissions data were taken from the oil sands study (ECCC, 2017).

Equation A3.2–17

$$ER_{i,j}^k = ER_{i,j}^{baseYr} \times \left(\frac{AF_j^k}{AF_j^{baseYr}} \right)$$

$ER_{i,j}^k$ = emission rate of compound i , source j , and year k , t/year

$ER_{i,j}^{baseYr}$ = base year (e.g. 2015) emission rate for compound i and source j , t/year

AF_j^k = activity values for source j and year k

AF_j^{baseYr} = base year (e.g. 2015) activity factor for source j

Activity Data

Table A3.2–25 lists the activity data used to estimate fugitive emissions for each oil sands operation and emission subcategory.

A3.2.2.6. Abandoned Oil and Gas Wells

When an oil or gas well reaches the end of its productive life, the well operator is required to properly abandon the well by removing all the equipment and plugging the well. This is done to prevent gas leakage from the well and to prevent the migration of oil and gas to the surrounding strata. However, CH₄ can be emitted into the atmosphere even when well abandonment best practices are followed. Additionally, abandoned wells that were not properly decommissioned exist. There are a number of reasons for this, including abandonment prior to the enactment of regulations and bankruptcy of the well owner.

There are two main categories of abandoned wells: plugged and unplugged wells. Unplugged wells are wells without recent production (i.e. inactive, temporarily abandoned/suspended or dormant) or without an operator (i.e. orphaned wells). Plugged wells are wells that have been plugged with cement or any mechanical plug to prevent migration of fluid. Emissions

result from both plugged and unplugged wells, but emissions from unplugged wells are significantly higher than emissions from plugged wells. Emissions may also vary depending on the type of production. However, due to data limitations, the approach described here does not differentiate on the basis of the type of production.

Estimation Methodology

A Tier 1 approach was used to estimate emissions from abandoned oil and gas wells using Equation A3.2–18.

Equation A3.2–18

$$ER_{ij}^k = \sum_{l=1}^n EF_{i,l} \times WellCount_{j,l}^k$$

ER_{ij}^k = emission rate of compound i , province j and year k , tonnes/year
 $EF_{i,l}$ = emission rate per abandoned well for compound i and well type l , tonnes/year
 $WellCount_{j,l}^k$ = well count for province j , well type l and year k

Emission Factors

The CH₄ emission factors used are the default EFs provided in the *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2019) which are based on measurements of emissions from abandoned oil and gas wells in the United States.

Table A3.2–26 shows the EFs used for estimating emissions for both abandoned oil and gas wells. The EFs are presented in terms of plugging status (i.e. plugged or unplugged) and location (i.e. onshore or offshore). For provinces where limited data is available on the well plugging status, the emission factor for all well types is used.

Activity Data

Annual counts of abandoned wells by province were developed using the data sources shown in Table A3.2–27.

The count of abandoned wells for each year of the time series was further subcategorized into well type (gas or oil), well status (plugged, unplugged or unknown) and location (onshore or offshore). Several assumptions were made to assign the plugging status of a well.

- An unplugged well is a well with a well status of suspended or inactive.
- A plugged well is a well with a well status of abandoned, downhole abandoned, or junked and abandoned.
- Any offshore well that is abandoned or not producing for an extended period is considered plugged.
- Where the plugging status could not be determined, it was considered unknown and a default emission factor was used to estimate emissions.

For the Northwest Territories and Nova Scotia, this level of disaggregation of activity data was not possible. For the Northwest Territories, there is no publicly available data on abandoned wells for oil and gas operations, and it was therefore difficult to evaluate the number of abandoned wells. For this reason, data from CAPP (CAPP, 2021) was used to estimate the abandoned well count. It was assumed that the abandoned well count is the difference between the total number of wells

Table A3.2–26 Emission Factors for Abandoned Oil and Gas Wells

Abandoned Well Type	Value (kg CH ₄ /well/yr) ^a	Uncertainty
Plugged wells (onshore)	0.02	-87% to +130%
Unplugged wells (onshore)	87.78	-99% to +150%
Plugged wells (offshore)	0.00035	-87% to +130%
Unplugged wells (offshore)	1.76	-99% to +150%
All well types (plugged and unplugged, onshore)	12.13	-83% to +124%
All well types (plugged and unplugged, offshore)	0.24	-83% to +124%

Notes:

a. IPCC (2019)

Table A3.2-27 Activity Data Required for Abandoned Oil and Gas Wells

Region	Source	Publication
AB	Alberta Energy Regulator	ST37: List of Wells in Alberta (AER, 2021g)
BC	British Columbia Oil and Gas Commission	Well Surface Hole Locations (BCOGC, 2021f)
SK	Saskatchewan Ministry of Energy and Resources	Abandoned well counts were provided upon request ^a
MB	Government of Manitoba: Oil & Gas	Petroleum Statistics, Unique Well Identifier Key List Report (MB, 2021b)
ON	Ontario Oil, Gas & Salt Resource Library	Petroleum Well Data (OGSRL, 2020)
NL	Canada–Newfoundland & Labrador Offshore Petroleum Board	Schedule of Wells Summary (CNLOPB, 2021h)
NS	Canada–Nova Scotia Offshore Petroleum Board	Cohasset Panuke production report (CNSOPB, 2019)
		Sable Offshore production report (CNSOPB, 2019)
		Deep Panuke production report (CNSOPB, 2019)
YT	Yukon Government: Energy Mines and Resources	Yukon Well Listing (YK, 2020)
NT	CAPP Statistical Handbook	Land, Exploration, Drilling Categories (CAPP, 2021)
		• Oil wells completed
		• Gas wells completed
		• Wells drilled
NB	New Brunswick Natural Resources and Energy Development	New Brunswick Well Listing (NB NRED, 2020)

Note:

a. Saskatchewan Ministry of Economy. 2021. Personal communication (email from Shevrov V., to Barrigar O., Pollutant Inventories and Reporting Division, Environment and Climate Change Canada, dated September 24, 2021).

drilled in the province and the number of oil and gas wells completed in the province. Following that, it is assumed that the average lifespan of completed wells is 20 years. For Nova Scotia, monthly production data by well was used to determine the abandonment date of the well. It was assumed that wells were abandoned six months after last production.

For the remaining provinces (i.e. Alberta, British Columbia, Saskatchewan, Yukon, Manitoba, New Brunswick, Newfoundland and Ontario), sufficient information was available in the provincial datasets to determine the number of abandoned wells by well type, well status and location.

Occasionally, the well type was not known. In this case, the emissions from these wells are allocated to oil or gas based on the known ratio of abandoned oil to gas wells in the same year.

A3.2.2.7. Flaring Special Case—Avoiding Double Counting

As defined in the *Report on Energy Supply and Demand in Canada* (Statistics Canada, 1990–), producer consumption “is the consumption by the producing industry of its own produced fuel—for example refined petroleum products consumed by the refined petroleum product industry, or natural gas used in the field, flared and waste, field uses, gathering uses, plant uses and metering adjustments.” Statistics Canada determines natural gas producer consumption volumes using administrative data provided by provinces and territories.

Combustion emissions from the consumption of producer-consumed fuels are estimated using the fuel volumes reported in the RESD (See Annex 3.1). Since flaring and venting emissions are estimated separately using the various fugitive models and reported as fugitives, it is necessary to subtract the volume of flared and vented gas, and the associated emissions, from the combustion estimates in order to avoid double counting, as described in section A3.1.4.1.2.

The provinces that have producer consumption of natural gas values in the RESD accounted for 99% of total crude oil production in Canada in 2020 and 99.9% of gross natural gas production. The volumes of gas reported as flared and vented are subtracted from producer consumption. In situations where flaring or venting emissions are estimated for a particular province that has no producer consumption reported in the RESD, the flaring emissions and associated natural gas volumes are not subtracted to ensure there is no underestimation of emissions.

Estimates for flaring emissions from petroleum refining are calculated using the refinery model (see A3.2.2.3). The volume of fuel flared is back-calculated from the flaring emissions and then subtracted from the producer consumption of still gas (also known as refinery fuel gas) since the method used by Statistics Canada to determine producer consumption of still gas is currently not well understood.

A3.3. Methodology for the Industrial Processes and Product Use Sector

The Industrial Processes and Product Use (IPPU) sector covers greenhouse gas (GHG) emissions arising from non-energy-related industrial activities. Categories included in this sector are Mineral Industry, Chemical Industry, Metal Industry, Non-energy Products from Fuels and Solvent Use, Electronics Industry, Product Uses as Substitutes for Ozone Depleting Substances (ODS), and Other Product Manufacture and Use. Chapter 4 presents methodological issues for each of these categories. This section of Annex 3 provides additional details on the methodologies used to estimate emissions in the following IPPU categories:

- Chemical Industry – Carbon dioxide (CO_2) emissions from Ammonia Production
- Metal Industry – CO_2 emissions from Iron and Steel Production
- CO_2 emissions from Non-Energy Products from Fuels and Solvent Use
- HFC emissions from Product Uses as Substitutes for ODS
- Other Product Manufacture and Use – Sulfur Hexafluoride (SF_6) emissions from Electrical Equipment

A3.3.1. CO_2 Emissions from Ammonia Production

Steam methane reforming (SMR), which generates hydrogen—an essential feedstock for the Haber-Bosch process in the production of ammonia (NH_3)—may use natural gas as the energy source to drive the process. Natural gas is also used as feedstock for the SMR process to provide a source of hydrogen. In both uses, the majority of carbon in natural gas ends up as CO_2 emissions. The source category 2.B.1, Ammonia Production, includes CO_2 emissions from the feedstock use of natural gas in the SMR process and emissions recovered for urea production. GHG emissions (CO_2 , nitrous oxide [N_2O], and methane [CH_4]) from the energy use of natural gas in SMR process and GHG emissions from fuels used in non-SMR ammonia production processes are accounted for in the Energy sector.

Facility-level data on feedstock use of natural gas and annual NH_3 production were obtained as part of Environment Canada's voluntary data collection for the years 2005 through 2009. These data were then used to develop the facility-level ammonia-to-feed fuel (conversion) factors that are applied to estimates natural gas used as feedstock for the years 1990 to 2017 (Equation A3.3–1). Of the nine plants in operation, seven (two of which have two SMR units each) provided ammonia-to-feed fuel factors. One of the two plants that did not provide information does not operate an SMR unit. These facility-level ammonia-to-feed fuel factors are considered confidential and are therefore not publicly available. However, based on the data collected, the average ammonia-to-feed fuel factor is 671 m³ of natural gas/tonne of NH_3 produced, and this average was used to estimate emissions from facilities that did not participate in the voluntary data collection. Furthermore, at plant level, the variability of ammonia-to-feed fuel factor is very stable (it varied less than 0.001% from year to year over the 5 surveyed years). Similarly, the average ammonia-to-feed fuel factor varied less than 0.001% from year to year over the 5 surveyed years.

For 2018 to 2020, natural gas feedstock values were facility-reported values obtained through the federal Greenhouse Gas Reporting Program (GHGRP).

Equation A3.3–1

$$\text{NG}_i = P_{\text{ammonia},i} \times FF_{\text{ammonia},i}$$

NG_i	=	natural gas consumed as feedstock in SMR facility i , m ³ natural gas
$P_{\text{ammonia},i}$	=	the annual production of NH_3 in SMR facility i , kt
$FF_{\text{ammonia},i}$	=	the ammonia-to-feed fuel factor of SMR facility i , m ³ natural gas/kt NH_3

The feedstock use (i.e., natural gas) for each facility is multiplied by their respective facility or province-specific natural gas carbon content and default carbon oxidation factor (COF) (IPCC, 2006) to determine the total facility generated carbon quantity. The national (gross) quantity of process CO_2 emissions from natural gas consumed as feedstock is then calculated by taking the sum of the facility generated carbon quantities. These steps are summarized in Equation A3.3–2. It is assumed that all carbon present in the feedstock is transformed to CO_2 (IPCC, 2006). Annual carbon content values for 2018 to 2020 were provided by each of the eight SMR facilities through the GHGRP. For 1990 to 2017, all eight active facilities confirmed carbon content values on a voluntary basis. Three facilities provided suitable average carbon content values for this time period. Two facilities provided annual facility-specific carbon content values for certain years of this time period and for the years where facility-specific values were unavailable, average carbon content values were used. One facility did not provide carbon content values over the 1990 to 2017 period and suggested the use of year- and

province-specific carbon contents; hence, internally developed values (see Annex 6) were used. The remaining two active facilities confirmed that the average facility-reported carbon content over 2018 to 2020 is suitable for use retroactively. For the three facilities that were shut down prior to 2018, the internally developed (year- and province-specific) natural gas carbon contents (see Annex 6).

Equation A3.3–2

$$\text{Generated CO}_2 = \sum_i \frac{44}{12} \times NG_i \times CC_i \times COF$$

Generated CO₂	=	national CO ₂ emissions generated, kt
<i>NG_i</i>	=	natural gas consumed as feedstock in SMR facility <i>i</i> , m ³ natural gas
<i>CC_i</i>	=	carbon content factor of the fuel in SMR facility <i>i</i> , kt carbon/m ³ natural gas
<i>COF</i>	=	carbon oxidation factor = 1 (unitless)
44/12	=	ratio of molecular weights, CO ₂ to carbon

The portion of national emissions recovered for use in urea production over the 1990 to 2017 time period is estimated using Equation A3.3–3, based on the assumption that urea production consumes a stoichiometric quantity of CO₂ and that 0.005 tonnes of CO₂ are emitted per tonne of urea produced. For 2018 to 2020, CO₂ consumed in the production of urea was directly reported by facilities.

Equation A3.3–3

$$\text{Recovered CO}_2 \text{ for Urea Production} = \sum_i P_{\text{urea},i} \times R$$

Recovered CO₂ for Urea Production	=	national recovered CO ₂ emissions from Urea Production, kt
<i>P_{urea,i}</i>	=	annual urea production of SMR facility <i>i</i> , kt urea
<i>R</i>	=	CO ₂ emissions recovery factor per unit mass of urea production where R = [M – L] = 0.728 t CO ₂ /t urea
<i>M</i>	=	stoichiometric mass ratio of CO ₂ required for urea production, 44/60 or 0.733 t CO ₂ /t urea
<i>L</i>	=	urea production process losses of CO ₂ , 0.005 t CO ₂ /t urea

The net national CO₂ emissions from NH₃ production are then calculated by subtracting the recovered CO₂ for urea production (quantified using in Equation A3.3–3 from 1990 to 2017) from the gross generated CO₂ emissions in Equation A3.3–2.

It should be noted that the quantity of natural gas feedstock used in the SMR process is subtracted from the overall non-energy use of natural gas, as reported by Statistics Canada, in order to estimate the residual (non-ammonia-related) process CO₂ emissions (refer to section A3.3.3, Non-energy Products from Fuels and Solvent Use).

The annual facility-level NH₃ production data for the years 1990 to 2017 were obtained from the following sources: 1990 to 2004 from the Cheminfo Services (2006) study; 2005 to 2009 from EC's voluntary data collection; and 2008 to 2017 from Statistics Canada's annual survey titled *Industrial Chemicals and Synthetic Resins* (Statistics Canada, 1990–2017).

Facility-level urea production data for the years 2008 through 2017 were also obtained from Statistics Canada's *Industrial Chemicals and Synthetic Resins* survey. Facility-level urea production values for earlier years (1990 through 2007) were estimated using the six-year average ratio of urea-to-ammonia production for the data years 2008–2013.

Facility-level NH₃ and urea production data were not used for years 2018 to 2020 as facility reported values of natural gas used as fuel and CO₂ consumed in urea production from the GHGRP were directly used.

A3.3.2. CO₂ Emissions from Iron and Steel Production

Canadian Iron and Steel Manufacturing Facilities

As of 2020, the Canadian steel sector consisted of 14 facilities, namely four integrated mills and 10 non-integrated mills (nine mini-mills and one ilmenite mill). Of the 14 facilities, eight are located in Ontario (including four integrated mills), three in Quebec and one in each of Alberta, Saskatchewan, and Manitoba. Table A3.3–1 provides a list of these facilities along with the type of manufacturing processes used.

Canadian Iron and Steel Process Technologies

Steel is produced in Canada by two main steelmaking processes (see Figure A3.3–1): basic oxygen furnaces and electric arc furnaces. The basic oxygen furnace is used in integrated mills in conjunction with coke making, sintering, and blast furnace iron-making operations. Integrated mills, which smelt iron ore and melt scraps, produce the greatest diversity of products, including bars, rods, structural shapes, plates, sheets, pipes and tubes, and wire rods. Although electric arc furnace technology is gaining importance, it is usually used in non-integrated mills (mini-mills or specialty steel mills) fed by scrap or direct reduced iron to produce a wide product range of carbon and alloy steels. ArcelorMittal Dofasco Inc. operates the only integrated steel plant in Canada that produces part of its steel by the electric arc furnace process. ArcelorMittal Contrecoeur operates the only Canadian steel mill that produces and uses direct reduced iron as part of its raw material feed. Ancillary or secondary steelmaking processes that are common to both integrated and non-integrated steelmaking include ladle metallurgy, continuous casting, hot forming, cold forming and finishing.

The following is a list of all process materials that are considered in the CO₂ emission estimates for CRF category 2.C.1, Iron and Steel Production.

- metallurgical coke (Statistics Canada, 1990–2020)
- pig iron production (Statistics Canada, 1990–2003, 2004–2012; CSPA, 2013–2017; GHGRP, 2018–2020)
- pig iron charge to steel furnace (including direct reduced) (Statistics Canada, 1990–2003, 2004–2012; CSPA, 2013–2017; GHGRP 2018–2020)
- scrap steel (own and purchased) (Statistics Canada, 1990–2003, 2004–2012; CSPA, 2013–2017; GHGRP, 2018–2020)
- limestone and dolomite use (NRCan, 1990–2006, 2007–2019)

Table A3.3–1 Iron, Steel and Ilmenite Smelting Facilities (2020)

Integrated Mills	
ArcelorMittal Dofasco	Hamilton, ON
Essar Steel Algoma	Sault Ste. Marie, ON
U.S. Steel Canada – Hamilton Works	Hamilton, ON
U.S. Steel Canada – Lake Erie Works	Nanticoke, ON
Mini-Mills ^{a,b}	
AltaSteel Ltd.	Edmonton, AB
ArcelorMittal Contrecoeur	Contrecoeur, QC
ArcelorMittal Contrecoeur – Ouest	Contrecoeur, QC
Valbruna ASW Steel	Welland, ON
EVRAZ North America	Regina, SK
Gerdau Ameristeel – Cambridge	Cambridge, ON
Gerdau Ameristeel Manitoba	Selkirk, MB
Gerdau Ameristeel – Whitby	Whitby, ON
Ivaco Inc.	L'Orignal, ON
Ilmenite Smelting Facility	
Rio Tinto – Fer et Titane Inc.	Sorel-Tracy, QC

Notes:

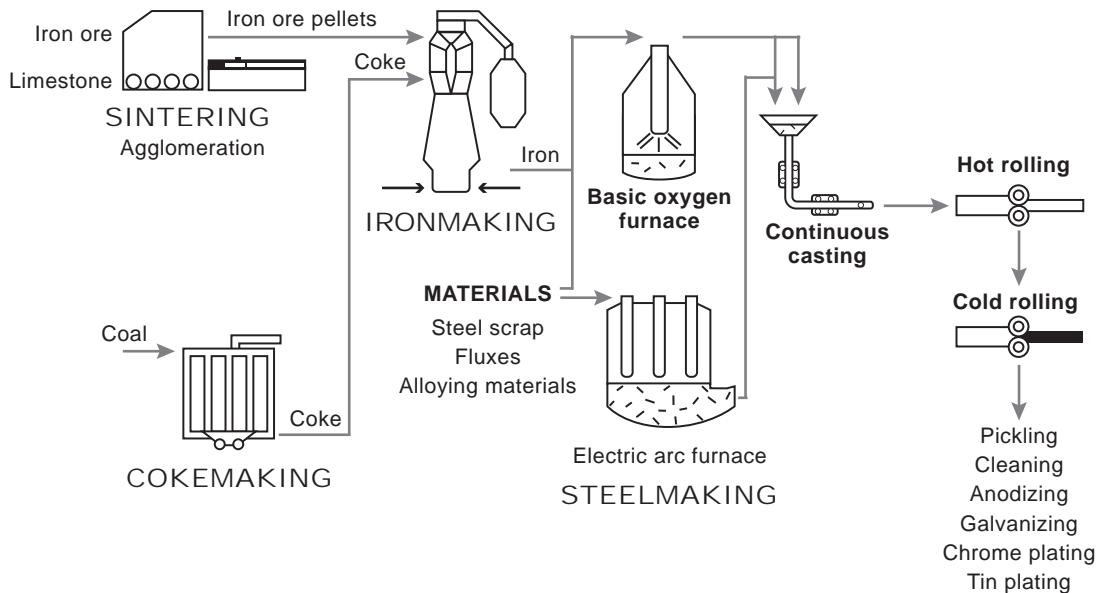
Information adapted from ECCC (2017).

a. Removed Mini-mill: Hamilton Specialty Bar Corp., Hamilton, ON, which closed permanently in 2018.

b. Added ASW Steel, Welland, ON, which is a small mini-mill that was excluded from the *Canada Gazette* notice.

Figure A3.3-1 Canadian Steelmaking Processes

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Emission factors and carbon contents applied are included in Annex 6.

Note that due to the integrated nature of the iron and steel facilities that manufacture coal-based metallurgical coke in Canada, it is currently not possible to disaggregate the data submitted by this industry for energy use. All emissions related to the use of metallurgical coke as a reagent for reduction of iron ore in the production of pig iron are allocated in CRF category 2.C.1. As illustrated in Chapter 4 (Equation 4–8), emissions from pig iron production are estimated on the basis of various parameters, including the mass of metallurgical coke used as a reductant and its respective emission factor.

Also note that CO₂ emissions from CRF category 2.C.2, Ferroalloys Production, are included in CRF category 2.C.1.a, Steel Production, since production of ferroalloys is a direct production of specialty steels from iron ore via the electric arc furnace process using reductants. However, disaggregation of the reductant portion (i.e., metallurgical coke) is not available and therefore these emissions are included in CRF category 2.C.1.b, Pig Iron Production.

A3.3.3. CO₂ Emissions from Non-Energy Products from Fuels and Solvent Use

Industrial activities in Canada that use fuel for non-energy purposes (e.g., feedstock material) include NH₃ production, petrochemical production, non-ferrous mining and processing, iron and steel production, and other chemical industries.

CO₂ emissions from non-energy use of hydrocarbons—which are not reported elsewhere in the inventory—are reported under the category of Non-energy Products from Fuels and Solvent Use. The emission estimates are based on non-energy fossil fuel use data collected by Statistics Canada (*Report on Energy Supply and Demand in Canada [RESD]* [Statistics Canada 1990–2020]) and aggregated by fuel type (e.g., natural gas, coke, butane, ethane, etc.) at the provincial/territorial level. Statistics Canada does not disaggregate this fuel data by industry or industrial activity, which means that without other supporting information, it is not possible to allocate this fuel data to a specific industry.

In some cases, Canada has obtained supporting information (e.g., through studies, surveys, other data sources, etc.) such that all or part of the non-energy fuel use data can be disaggregated and allocated to the appropriate source category. Allocation of non-energy fuel use data to specific source categories is possible for the following industrial activities:

- natural gas used to produce hydrogen for NH₃ production
- various fuels used as feedstock in the production of petrochemicals (methanol, ethylene and ethylene dichloride)
- carbon anodes used to electrically reduce alumina to aluminium in the aluminium production process
- coke used in iron and steel production

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For these industrial activities, known or estimated non-energy fuel types and quantities are used in estimating emissions. The known or estimated fuel quantities are then subtracted from the RESD non-energy fuel use data, and the remaining (residual) fuel quantities represent the non-energy fuel used by other industries. This avoids double counting of emissions and improves transparency in the inventory.

To estimate emissions, average national level CO₂ emission factors are available for each fuel type and are applied to the total non-energy fuel quantities (or residual quantities, if applicable) at the provincial/territorial level. Provincial/territorial estimates are then aggregated to provide a national total for CRF source category 2.D, Non-energy Products from Fuels and Solvent Use.

The following describes the methods used to estimate emissions for each category of non-energy use of fossil fuels (gaseous, solid and liquid fuels) and, where possible/applicable, explains how emissions are disaggregated and allocated to specific source categories (previously mentioned) in order to avoid double counting of emissions.

Gaseous Fuels

The only gaseous fuel considered in this category is natural gas. Natural gas can be used for methanol and thermal carbon black production; however, a large portion is used in the SMR process to manufacture NH₃.

CO₂ emissions from NH₃ production and methanol production are estimated and reported in CRF source categories 2.B.1 and 2.B.8.a, respectively. The quantities of natural gas used as feedstock in NH₃ and methanol manufacturing are subtracted from the RESD's overall non-energy natural gas to determine the remaining (residual) quantity of non-energy natural gas.

Based on a study conducted in 2005 (Chemininfo Services, 2005a), a CO₂ emission factor for the residual non-energy use of natural gas was developed (38 g CO₂/m³) and applied to the residual non-energy natural gas quantity to estimate emissions from this source.

Note that emissions arising from non-energy use of natural gas to produce hydrogen in the oil refining and bitumen industries are allocated to the Energy sector of the inventory.

Solid Fuels

Solid fuels considered in the Non-energy Products from Fuels and Solvent Use category are:

- Canadian bituminous coal
- sub-bituminous coal
- foreign bituminous coal
- lignite
- anthracite
- metallurgical coke
- petroleum coke

CO₂ emissions from the non-energy use of these solid fuels are determined by applying the fuel-, province- and/or year-specific emission factors presented in tables A6.1–6, A6.1–9 and A6.1–10 of Annex 6 for petroleum coke, coal and metallurgical coke (coke from coal), respectively, to the RESD data.

The emission factors used for estimating releases of CO₂ from the non-energy use of coal are the same as those for combustion; it is assumed that 100% of the carbon in these products will eventually be oxidized and emitted as CO₂.

CO₂ emissions resulting from the consumption of electrodes in the aluminium industry are reported in CRF source category 2.C.3, Aluminium Production. A key fuel used to make electrodes for the aluminium industry is petroleum coke. Non-energy coke is also used to make electrodes used in electric arc furnaces in the iron and steel industry (CRF source category 2.C.1, Iron and Steel Production). The quantities of petroleum coke used in the aluminium industry and iron and steel industry are subtracted from the RESD's overall non-energy use of petroleum coke. The CO₂ emissions from the residual non-energy petroleum coke use are calculated by applying the emission factors provided in Table A6.1–6 of Annex 6.

Liquid Fuels

In addition to the emissions from gaseous and solid fuels, CO₂ emissions from the non-energy use of liquid fuels (natural gas liquids (NGLs), oil refinery petrochemical feedstocks and lubricants) are also reported in CRF category 2.D, Non-energy Products from Fuels and Solvent Use.

CO₂ emissions resulting from the use of liquid fuels (feedstock use) in the production of ethylene are estimated and reported in CRF source category 2.B.8.b. The quantities of liquid fuels (specifically propane, butane, ethane, petrochemical feedstocks) used as feedstock in the production of ethylene are subtracted from the RESD's overall non-energy liquid fuels. The remaining quantities of non-energy liquid fuels are multiplied by the corresponding emission factors, as shown in Table A6.2–9 in Annex 6 to estimate CO₂ emissions from this source.

It should also be noted that, owing to the way in which energy statistics are currently collected in Canada, a portion of non-energy use of liquid fuels has been reported under energy use, which is accounted for in the Energy sector.

In the case of the residual non-energy use of NGLs—i.e., residual of petrochemical production use—the emission factors provided in the McCann (2000) study assume that all the carbon is oxidized and are presented in Table A6.2–9 in Annex 6.

The residual and non-residual non-energy use of petroleum products coming out of the oil refineries (i.e., petrochemical feedstocks, naphthas, lubricants, greases and other petroleum products) also results in CO₂ emissions and is accounted for in the Non-energy Products from Fuels and Solvent Use category. Derivations of the non-energy use emission factors are shown in Table A6.2–9 in Annex 6. To estimate emissions at national and provincial/territorial levels, the volume of non-energy product used is multiplied by its corresponding emission factor.

A3.3.4. HFC Emissions from Product Uses as Substitutes for Ozone Depleting Substances

A3.3.4.1. Activity Data

HFC emission estimates for 1995 were based on data gathered from an initial HFC survey conducted by EC in 1996.¹⁰ The Department revised subsequent surveys to obtain more detailed activity data for later years. The 1998, 1999, 2001 and 2005 HFC surveys were the source of activity data for emission estimates for the years 1996–2000 and 2004 (2004–2006 emails from Y. Bovet and Y. Guilbault).¹¹ In some cases, one survey was done to collect data for two years. HFC sales data for 2001–2003 were also collected in 2005 from major HFC importers in Canada (Chemininfo Services, 2005b). These data were provided by market segment, such that the total quantity used for each type of application could be determined. HFC import and sales data for 2005–2010¹² were collected by EC through a voluntary data submission process, whereby requests for data were sent to the main importers of bulk HFCs and to companies that import or export manufactured items containing HFCs. For 2009, the distribution list for data collection was expanded, as EC became aware of other importers and exporters in the market (either importers of bulk HFCs or importers or exporters of manufactured items containing HFCs) by looking at HFC import data collected by the Canada Border Services Agency (CBSA).¹³ Information on HFC-245fa received in these surveys were incorporated for bulk HFCs from 2001 to 2007 and for manufactured items containing HFCs for 2010. Data sets from 1995 to 2000 were verified for use, import and export of HFC-245fa, and no instances were found. Where data were unavailable, the quantities were extrapolated to the current inventory year.

In 2014, EC performed a mandatory survey of bulk importers for the data years 2008 to 2012, and the results of the survey (ECCC, 2015a) were incorporated into the inventory. Where duplicate reporting occurred between the mandatory and voluntary surveys, the mandatory survey was chosen for the inventory due to the legal reporting requirements.

In 2016, Environment and Climate Change Canada (ECCC) performed mandatory surveys of bulk importers (ECCC, 2016a, 2016b) for the data years 2013–2014 and 2015, which have been included in the inventory. No surveys were performed for the 2016 data year.

¹⁰ Bovet Y, Guilbault Y. 2004–2006. Personal communications (emails received from Bovet Y and Guilbault Y to Au A, Greenhouse Gas Division, during the years 2004–2006). Use Patterns and Control Implementation Section.

¹¹ Bovet Y, Guilbault Y. 2004–2006. Personal communications (emails received from Bovet Y and Guilbault Y to Au A, Greenhouse Gas Division, during the years 2004–2006). Use Patterns and Control Implementation Section.

¹² Except for 2010, data collected by EC on bulk HFCs only covered sales. However, with no Canadian production existing for HFCs and an insignificant amount of exports, the import values should theoretically be close to the sales values.

¹³ It should be noted that HFC data from the CBSA cannot be used for GHG inventory purposes, as they are collected and categorized only under three types: HFC-134a, HFC-152a and others. Also, the data are not presented by use type. However, company-specific data from the CBSA are a useful tool for data verification and for expanding the distribution list for HFC data collection.

In 2018, 2019, 2020 and 2021, ECCC collected bulk import and export HFC data for the data years 2017, 2018, 2019 and 2020 respectively, under the mandatory reporting system set out under the *Ozone-depleting Substances and Halocarbon Alternatives Regulations* (ODS Regulations), which came into force December 29, 2016 (ECCC, 2021). Updates to the mandatory reports for the data years 2017–2019 were also received and implemented in this submission.

Table A3.3–2 shows the years where there are activity data for bulk HFC imports and exports, the years when the activity data were collected, and the source of the data. Table A3.3–3 shows the years where there are activity data for imported and exported manufactured items containing HFCs, the years when the activity data were collected, and the source of the data.

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Table A3.3–2 Years of Activity Data for Bulk HFC Imports and Exports, Years of Collection, and Data Source

Data Year	Data Collection Year	Data Source
1995	1996	Mandatory survey from UPCIS
1996	1998	Mandatory survey from UPCIS
1997	1998	Mandatory survey from UPCIS
1998	1999	Mandatory survey from UPCIS
1999	2001	Mandatory survey from UPCIS
2000	2001	Mandatory survey from UPCIS
2001	2005	Voluntary survey from Cheminfo Services
2002	2005	Voluntary survey from Cheminfo Services
2003	2005	Voluntary survey from Cheminfo Services
2004	2005	Mandatory survey from UPCIS
2008	2014	Mandatory survey from section 71 of CEPA 1999
2009	2014	Mandatory survey from section 71 of CEPA 1999
2010	2014	Mandatory survey from section 71 of CEPA 1999
2011	2014	Mandatory survey from section 71 of CEPA 1999
2012	2014	Mandatory survey from section 71 of CEPA 1999
2013	2016	Mandatory survey from section 71 of CEPA 1999
2014	2016	Mandatory survey from section 71 of CEPA 1999
2015	2016	Mandatory survey from section 71 of CEPA 1999
2017	2018	Mandatory survey from ODS Regulations of CEPA 1999
2018	2019	Mandatory survey from ODS Regulations of CEPA 1999
2019	2020	Mandatory survey from ODS Regulations of CEPA 1999
2020	2021	Mandatory survey from ODS Regulations of CEPA 1999

Table A3.3–3 Years of Activity Data for Imported and Exported Manufactured Items Containing HFCs, Years of Collection, and Data Source

Data Year	Data Collection Year	Data Source
1996	1998	Mandatory survey from UPCIS
1997	1998	Mandatory survey from UPCIS
1998	1999	Mandatory survey from UPCIS
2004	2005	Mandatory survey from UPCIS
2005	2006	Voluntary survey from UPCIS
2006	2007	Voluntary survey from UPCIS
2007	2008	Voluntary survey from UPCIS
2008	2009	Voluntary survey from UPCIS and voluntary additional data from section 71 mandatory survey of CEPA 1999
2009	2010	Voluntary survey from UPCIS and voluntary additional data from section 71 mandatory survey of CEPA 1999
2010	2011	Voluntary survey from UPCIS and voluntary additional data from section 71 mandatory survey of CEPA 1999
2011	2014	Voluntary additional data from section 71 mandatory survey of CEPA 1999
2012	2014	Voluntary additional data from section 71 mandatory survey of CEPA 1999
2013	2016	Voluntary additional data from section 71 mandatory survey of CEPA 1999
2014	2016	Voluntary additional data from section 71 mandatory survey of CEPA 1999
2015	2016	Voluntary additional data from section 71 mandatory survey of CEPA 1999

A3.3.4.2. Methodology

Canada uses a detailed sector breakdown of HFC sub-applications (Table A3.3–4), requiring that the HFC use data be broken down at this level annually. To meet this requirement, missing data had to be filled in, and data collected at an application level had to be broken down to sub-application levels.

A variety of techniques were used to fill in the data gaps from reporters between voluntary surveys. For instance, when a company did not report in subsequent years, the data were held constant. Another technique employed for years in which no surveys were performed (e.g., imports/exports of manufactured items from 1999 to 2003) was the use of linear interpolation to estimate the missing data.

Table A3.3–4 Canadian HFC Applications and Sub-Applications

Application/Sub-Application Description
Aerosols
Personal care products
Pharmaceutical products
Medical products
Household products
Mining application products
Commercial/industrial products
Blowing Agent in Foams
Cushioning – automobiles (seats, roof, etc.)
Cushioning – other (furniture, mattresses, etc.)
Thermal insulation – homes and buildings
Thermal insulation – pipes
Thermal insulation – refrigerators and freezers
Thermal insulation – other (specify)
Packaging – food (specify)
Packaging – non-food (specify)
Other foam uses (specify)
Air Conditioning (Original Equipment Manufacture)
Air conditioner units in motor vehicles
Chillers (specify centrifugal or reciprocating)
Residential (air conditioners, dehumidifiers, etc.)
Air Conditioning (Service/Maintenance)
Air conditioner units in motor vehicles
Chillers (specify centrifugal or reciprocating)
Residential (air conditioners, dehumidifiers, etc.)
Refrigeration (Original Equipment Manufacture)
Commercial transport
Commercial and institutional (retail foods, vending machines, etc.)
Industrial (warehouses, process equipment, etc.)
Residential (freezers, refrigerators)
Other equipment (specify)
Refrigeration (Service/Maintenance)
Commercial transport
Commercial and institutional (retail foods, vending machines, etc.)
Industrial (warehouses, processes, etc.)
Residential (refrigerators, freezers, etc.)
Other equipment (specify)
Solvent
Electronic industry
Metal cleaning/drying
Dry cleaning
Laboratory solvent
General cleaning (specify)
Fire Suppression/Extinguishing Systems (Original Equipment Manufacture)
Portable (mobile) systems
Total flooding (fixed) systems
Fire Suppression/Extinguishing Systems (Service/Maintenance)
Portable (mobile) systems
Total flooding (fixed) systems
Miscellaneous
Hospital/institutional sterilizing
Leak testing
Other (Specify)

Table A3.3–5 **Proxy Variables Used for HFC Trend Extrapolation**

Proxy Variable Description
Commercial floor space
Residential floor space
Population
Gross domestic product
Gross output for the following categories:
Computer and Electronic Products Manufacturing
Fabricated Metal Products
Food
Furniture and Related Products
Health Care and Social Assistance
Mining (excluding Oil, Gas and Coal)
Other Manufacturing
Other Services (excluding Public Administration)
Professional, Scientific and Technical Services
Transportation Equipment

To meet the requirements of a Tier 2 methodology, ECCC used two approaches to break down the 1995 to 2004 application-level data to the sub-application level. In a given year, the HFCs reported at an application level were broken down based on the proportions of the corresponding sub-application levels if a large amount of HFCs were reported in those corresponding sub-application levels in the same year. If sufficient breakdown was not available for the year and application level, the breakdown from the closest historical year for the same HFC and application level was used.

For the 2008 to 2012 mandatory survey data, the HFCs reported at an application level were broken down based on the 2004 breakdown. The 2004 data were used because the breakdown for this year was the most complete and is currently the best information available. For the 2013 to 2015 data from the mandatory surveys, the HFCs reported at an application level were broken down to sub-application levels based on the 2012 breakdown and, when sufficient information was not available, on the 2004 breakdown. For some of the 2008–2015 data, when bulk importers had initially only reported HFCs (by HFC type) without specifying the associated applications or sub-applications, the surveyed bulk importers were asked to provide, to the best of their knowledge, a list of sub-application levels for the reported HFCs. This list of sub-applications was then used by ECCC to evenly distribute the reported HFC quantities.

For the 2017 to 2020 bulk import and export data collected under the ODS Regulations, all the reported data needed to be broken down to sub-application levels. The 2015 breakdown was determined to be the most appropriate because it was the most recent mandatory survey where breakdowns by sub-application were available.

For the information on new HFCs received under the ODS Regulations, existing breakdowns of an application to the sub-application level of other HFCs (generally HFC-134a) were used.

The bulk import and export data collected through voluntary submission for the 2005 to 2007 data years were considered incomplete and were therefore estimated using linear interpolation between the 2004 and 2008 data years.

The 1995 data on the quantities of HFCs contained in imported and exported manufactured items, except imported and exported vehicles, were not available. Therefore, the 1996 to 1998 results were used to linearly extrapolate back to 1995. For 1999–2003, these quantities were linearly interpolated from the data available in 1998 and 2004.

The data were reviewed with respect to time series consistency according to Volume 1, Chapter 5, Section 5.3.3.4 of the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006) and some gaps were noted for data on bulk imports and exports and on imported and exported manufactured items containing HFCs. The 2016 data year is a year for which bulk import and export data do not exist, and the 2011 to 2020 data years are years for which a complete set of data on imported and exported manufactured items containing HFCs does not exist. Extrapolation using proxy variables were applied to fill in the data gaps as required. Table A3.3–5 lists the various proxy variables applied for the extrapolation process.

A3.3.4.3. Emission Factors and Lifetimes

In 2013, EC conducted a survey of the air-conditioning and refrigeration applications to obtain information for developing emission factors.

The information was reviewed (EHS, 2013; ECCC, 2015b), in accordance with the quality control measures set out in Volume 1, Chapter 6, Section 6.7.1.2 of IPCC 2006 Guidelines (IPCC, 2006). The emission factors developed using the collected information were also compared to default emission factors published in Table 7.9 of Volume 3, Chapter 7 of IPCC 2006 Guidelines and most were found to be within the same range. Some emission factors (e.g. end-of-life decommissioning)

did not meet the quality control checks from Volume 1, Chapter 6, Section 6.7.1.2 of IPCC 2006 Guidelines for expert elicitation; values were therefore chosen within the range of emission factors published in Table 7.9 of Volume 3, Chapter 7 of IPCC 2006 Guidelines, guided by other information such as the regulatory environment in Canada. These emission factors have been applied to the whole time series from 1995 onwards.

The emission factors for the sub-application of “Other equipment” under Refrigeration—a mix of specialty applications—were derived through a weighted average of the emission factors from the other specific refrigeration sub-applications.

For the air conditioning and refrigeration applications, the expected lifetimes applied in the emission estimations were chosen based on the survey results and the information published in Table 7.9 of Volume 3, Chapter 7 of IPCC 2006 Guidelines.

For the remaining HFC applications, emission factors and lifetimes were chosen from Volume 3, Chapter 7 of IPCC 2006 Guidelines.

Table A6.2–11 in Annex 6 presents the emission factors used to estimate the HFC emissions.

A3.3.4.4. Emission Estimations

The net consumption of a HFC in a specific sub-application are calculated using Equation A3.3–4. This equation is a modified version of Equation 7.1 from Volume 3, Chapter 7 of IPCC 2006 Guidelines that has been adapted to the Canadian context. The total quantity of each HFC that remains in products after assembly, in-service and end-of-life losses, also known as a HFC bank, is also calculated.

Equation A3.3–4

$$C_{net,i} = IM_{bulk,i} + IM_{manufacture,i} - EX_{manufacture,i}$$

$C_{net,i}$	=	net consumption of HFC i , kg
$IM_{bulk,i}$	=	imports of bulk of HFC i , kg
$IM_{manufacture,i}$	=	imports of manufactured items of HFC i , kg
$EX_{manufacture,i}$	=	exports of manufactured items of HFC i , kg

Annual emissions for each applicable lifecycle stage are estimated for each sub-application by multiplying the HFC quantity in that stage by its corresponding emission factor. It is assumed that once an item is manufactured, the technology and its inherent in-service emissions rate will remain constant throughout its lifetime. The in-service emission estimate takes into consideration the quantity of HFC that has already been emitted during the assembly stage. Likewise, the emission estimate from the end-of-life of the product is based on the quantity of HFC available after the assembly and in-service emissions have taken place and on the corresponding emission factor for the sub-application. The end-of-life emission factor used also considers regulations in place at the time of decommissioning.

The following sections explain the HFC emission estimation equations applied for each unique application/sub-application in more detail.

A3.3.4.4.1. HFC Emissions from Aerosols

HFC emissions from aerosols application are estimated using Equation A3.3–5, which is Equation 7.6 from Volume 3, Chapter 7 of IPCC 2006 Guidelines.

Equation A3.3–5

$$EA_t = (A_t \times EF_A) + (A_{t-1} \times (1 - EF_A))$$

EA_t	=	emissions from aerosols in year t , tonnes
A_t	=	quantity of HFC contained in aerosol products sold in year t , tonnes
A_{t-1}	=	quantity of HFC contained in aerosol products sold in year $t-1$, tonnes
EF_A	=	in-service emission factor for aerosols, fraction

A3.3.4.4.2. HFC Emissions from Blowing Agent in Open-Cell Foams

HFC emissions from open-cell foam blowing are estimated using Equation A3.3–6, which is Equation 7.8 from Volume 3, Chapter 7 of IPCC 2006 Guidelines.

Equation A3.3–6

$$EOCF_t = M_t$$

$EOCF_t$	=	emissions from blowing agent in open-cell foams in year t , tonnes
M_t	=	quantity of HFC used in manufacturing new open-cell foams in year t , tonnes

A3.3.4.4.3. HFC Emissions from Blowing Agent in Closed-Cell Foams

HFC emissions from closed-cell foam blowing are estimated using Equation A3.3–7, which is a modified version of Equation 7.7 from Volume 3, Chapter 7 of IPCC 2006 Guidelines. The reason for the modification is that no information on recovery and destruction of HFCs in closed-cell foams and their blowing agents is available.

Equation A3.3–7

$$ECCF_t = (CCF_t \times (EF_A + EF_{IS})) + (CCFBank_{t-n} \times EF_{IS}) + (DL_t \times EF_{EOL})$$

$ECCF_t$	=	emissions from blowing agent in closed-cell foams in year t , tonnes
CCF_t	=	quantity of HFC used in manufacturing new closed-cell foams in year t , tonnes
EF_A	=	assembly emission factor for closed-cell foams, fraction
$CCFBank_{t-n}$	=	quantity of HFC charged into closed-cell foam manufacturing between year t and year $t-n$, tonnes
EF_{IS}	=	in-service emission factor for closed-cell foams, fraction
DL_t	=	decommissioning losses in year t = remaining losses of HFC at the end of service life that occur when the product/equipment is scrapped, tonnes
EF_{EOL}	=	end-of-life emission factor for closed-cell foams, fraction
n	=	product lifetime of closed-cell foam
t	=	current year

A3.3.4.4.4. HFC Emissions from Air Conditioners and Refrigerators Manufactured in Canada

HFC emissions from air conditioning and refrigeration equipment manufactured in Canada are estimated using Equation A3.3–8, which is a modified version of Equation 7.10 from Volume 3, Chapter 7 of IPCC 2006 Guidelines.

Equation A3.3–8

$$EACROEM_t = (ACROEM_t \times (EF_A + EF_{IS})) + (ACROEMBank_{t-n} \times EF_{IS}) + (DL_t \times EF_{EOL})$$

$EACROEM_t$	=	emissions from air conditioners or refrigerators manufactured in Canada in year t , tonnes
$ACROEM_t$	=	quantity of HFC used in manufacturing new air conditioners or new refrigerators in year t , tonnes
EF_A	=	assembly emission factor for new air conditioners or new refrigerators, fraction
$ACROEMBank_{t-n}$	=	quantity of HFC charged into air conditioners or refrigerators between year t and year $t-n$, tonnes
EF_{IS}	=	in-service emission factor for air conditioners or refrigerators, fraction
DL_t	=	decommissioning losses in year t = remaining losses of HFC at the end of service life that occur when the air conditioner or refrigerator is scrapped, tonnes
EF_{EOL}	=	end-of-life emission factor for air conditioners or refrigerators, fraction
n	=	product lifetime of air conditioner or refrigerator
t	=	current year

A3.3.4.4.5. HFC Emissions from Air Conditioners and Refrigerators Manufactured Elsewhere

Equation A3.3–8 is applied for estimating HFC emissions from air conditioners and refrigerators manufactured elsewhere, except that the assembly emission factor in this case is zero.

A3.3.4.4.6. HFC Emissions from Solvents

HFC emissions from solvents are estimated using Equation A3.3–9, which is a modified version of Equation 7.5 from Volume 3, Chapter 7 of IPCC 2006 Guidelines. The reason for the modification is that no information on destruction of HFCs used as solvents is available.

Equation A3.3–9

$$ES_t = (S_t \times EF_s) + (S_{t-1} \times (1 - EF_s))$$

ES_t	=	emissions from solvents in year t , tonnes
S_t	=	quantity of HFC contained in solvents sold in year t , tonnes
S_{t-1}	=	quantity of HFC contained in solvents sold in year $t-1$, tonnes
EF_s	=	in-service emission factor for solvents, fraction

A3.3.4.4.7. HFC Emissions from Fire Suppression and Extinguishing Systems

HFC emissions from fire suppression/extinguishing systems are estimated using Equation A3.3–10, which is a modified version of Equation 7.17 from Volume 3, Chapter 7 of IPCC 2006 Guidelines. The reason for the modification is that no information on the destruction of HFCs used in fire suppression and extinguishing systems is available.

Equation A3.3–10

$$EFSES_t = ((FSES_t + FSESBank_{t-n}) \times EF_{IS}) + (DL_t \times EF_{EOL})$$

$EFSES_t$	=	emissions from fire suppression and extinguishing systems in year t , tonnes
$FSES_t$	=	quantity of HFC used in fire suppression and extinguishing systems in year t , tonnes
$FSESBank_{t-n}$	=	quantity of HFC charged into fire suppression and extinguishing systems between year t and year $t-n$, tonnes
EF_{IS}	=	in-service emission factor for fire suppression and extinguishing systems, fraction
DL_t	=	decommissioning losses in year t = remaining losses of HFC at the end of service life that occur when the fire suppression and extinguishing system is scrapped, tonnes
EF_{EOL}	=	end-of-life emission factor for fire suppression and extinguishing systems, fraction
n	=	product lifetime of fire suppression and extinguishing system
t	=	current year

A3.3.4.4.8. HFC Emissions from Miscellaneous and Other Applications

HFC emissions from miscellaneous and other applications are estimated using Equation A3.3–11, which is Equation 7.18 from Volume 3, Chapter 7 of IPCC 2006 Guidelines.

Equation A3.3–11

$$EMOA_t = (MOA_t \times EF_{MOA}) + (MOA_{t-1} \times (1 - EF_{MOA}))$$

$EMOA_t$	=	emissions from miscellaneous and other applications in year t , tonnes
MOA_t	=	quantity of HFC contained in miscellaneous and other products sold in year t , tonnes
MOA_{t-1}	=	quantity of HFC contained in miscellaneous and other products sold in year $t-1$, tonnes
EF_{MOA}	=	in-service emission factor for miscellaneous and other products, fraction

A3.3.4.4.9. Total Annual HFC Emission Estimations

The total annual emission estimates for each HFC are derived by summing the emissions from all applicable applications. Once the total annual emission estimates at the national level are obtained, they are distributed by province/territory based on proxy variables, such as gross output of accommodation and food services for commercial refrigeration and number of households for residential refrigeration.

A3.3.5. SF₆ Emissions from Electrical Equipment

A3.3.5.1. Methodology—Derivation of the Country-Specific Quantification Method

To quantify SF₆ emissions (for 2006–2020), the Canadian electricity industry uses a method derived from the basic Tier 3 IPCC 2006 Guidelines life-cycle Equation 8.10 (Volume 3), as explained in the following sections.

A3.3.5.1.1. Equipment Manufacturing Emissions

According to some utilities, electrical equipment purchased by the Canadian electricity sector is manufactured in the United States, Europe or Asia and hence emissions associated with manufacturing would have occurred mainly outside of Canada.

A3.3.5.1.2. Equipment Installation Emissions

SF₆ equipment is delivered to utilities pre-charged with some SF₆ and charged to full capacity at the time of installation. In the Canadian electricity industry, the potential for SF₆ emissions during equipment installation is considered to be extremely low. A vacuum hold check is typically performed prior to the installation of new equipment to ensure that the equipment is gas tight.

A3.3.5.1.3. Equipment Use Emissions

The primary source of SF₆ releases is associated with the cumulative minute releases that occur during normal equipment operation. Gas releases could potentially occur during gas handling and transfer operations, although such releases would be significantly smaller in magnitude than emissions that occur during normal operations.

Due to the SF₆ leakage that occurs during the above circumstances, utilities are required to “top-up” their equipment to keep it properly charged and operational. By topping up equipment with SF₆ gas, utilities are able to replace the amount of gas that has escaped.

A3.3.5.1.4. Equipment Decommissioning and Failure Emissions

During the decommissioning of retired equipment, SF₆ gas must be recovered from the retired equipment prior to disposal. As SF₆ gas releases may occur as a result of the way in which the gas is transferred out of the equipment during gas recovery, decommissioning of retired equipment becomes a potential source of SF₆ releases.

When catastrophic failures of equipment occur, a significant amount of SF₆ leaks out of the equipment. Equipment damage is therefore a potential source of emissions.

Retired equipment and damaged equipment that cannot be repaired are sent off-site for disposal.

A3.3.5.1.5. Emissions from SF₆ Recycling

When SF₆ gas is recovered from equipment, it is filtered through a gas cart or other filtering equipment to remove moisture and impurities before it is reused. When SF₆ gas has been contaminated with air and impurities and has a purity of less than a certain level (the acceptable level can vary between 95% and 99%, depending on utility practices), it cannot be reused and is sent for off-site purification in the United States. There are no facilities in Canada that perform SF₆ gas purification. One of the methods utilized to purify SF₆ gas is the use of a cryogenic process to separate and remove the air/nitrogen from the SF₆ gas. The purification of SF₆ gas does not produce SF₆ emissions. Hence, emissions from SF₆ recycling are eliminated from the calculation of total emissions.

Given the reasoning above, the Canadian electricity industry uses a modified, country-specific Tier 3 IPCC approach to estimate SF₆ releases. Only emissions from equipment use and equipment decommissioning and failure are calculated, as shown in Equation A3.3–12.

Equation A3.3–12

$$\begin{aligned} \text{Total utility SF}_6 \text{ emissions} = \\ \Sigma \text{Equipment use emissions} + \Sigma \text{Equipment decommissioning and failure emissions} \end{aligned}$$

A3.3.5.2. Methodology—Quantifying Equipment Use Emissions

Emissions that occur during equipment use are a result of leakages during gas transfer and handling operations and during normal operation of the equipment. In order to keep equipment properly charged and operational, utilities must fill their equipment to replace the amount that has escaped. This amount is referred to as a “top-up.”

Leakages of SF₆ are also seen during maintenance/repair activities. When equipment needs to be repaired or sent for maintenance, the SF₆ gas is recovered from it and, once the equipment is repaired, it is refilled with the SF₆ gas that was recovered. There will be an additional amount needed to refill the equipment, since some gas may have escaped due to normal operations and during the transfer of the recovered gas from the equipment to gas carts (or storage cylinders) and back to the equipment. It is this additional/incremental amount of SF₆ gas that is referred to as the “top-up.” Hence, an accurate estimate of the amount of SF₆ released is the amount used by utilities to top up their equipment during the equipment use stage.

A3.3.5.2.1. Options for Tracking SF₆ Consumed for Top-ups

The following is a list of options for Canadian electric utilities to track the amount of SF₆ that is used for top-up purposes in order to quantify emissions of SF₆ from the equipment use phase. These options are listed in order of most accurate to least accurate. The most accurate method involves directly measuring the amount of gas transferred during top-ups, and the less accurate methods involve utilities relying on inventory records or purchase receipts to obtain an estimate. Each utility will have discretion over which method to use. Canadian electric utilities may track the amount of SF₆ that is used annually for top-up purposes (i.e., the amount that has been emitted) by using mass flow meters or a mass balance, or by counting the number of cylinders consumed.

For all of these tracking options, it is assumed that the quantities of SF₆ tracked do not include the gas used to pressurize the new switchgear to its full capacity at time of installation. Quantities of gas used for pressurization are typically provided by the switchgear vendor at time of installation and hence do not come out of the utility inventory (see also A3.3.5.1.2, Equipment Installation Emissions).

Option 1: Mass Flow Meters

Mass flow meters provide the most accurate method for measuring the quantity of SF₆ consumed during each equipment top-up operation. The sum of all measured quantities during top-up operations will be used to determine the equipment use emissions.

Option 2: Mass Balance

Utilities may choose to weigh their SF₆ cylinders to determine the quantity of SF₆ consumed for top-up operations. The difference in mass of the cylinders can be determined either every time there is an equipment top-up operation or on an inventory basis. Utilities must also account for any purchases or additions to the inventory, the weight of SF₆ cylinders returned to suppliers, and the quantity of SF₆ sent off-site for recycling or destruction during the year. When using a mass balance, utilities should ensure that the accuracy of the weigh scale is compatible with the weight of the cylinders to be weighed. For example, utilities should use a scale accurate to ±1 kg, rather than ± 5 kg, to weigh a 50-kg cylinder.

Option 3: Cylinder Count

In the absence of mass flow meters or weigh scales, utilities may choose to rely on information from supplier or inventory records and from purchase receipts to obtain the number and weight of SF₆ cylinders purchased for top-up purposes. The mass of SF₆ consumed can be assumed to be equal to the amount of SF₆ purchased in a year or equal to the change in maintenance inventory.

The weight of SF₆ found in different types of cylinders should be known. Therefore, utilities can simply obtain the weight of SF₆ consumed for top-up purposes by performing a cylinder count. If more than one type of cylinder is used, utilities must ensure that the number of cylinders of each type is multiplied by the cylinder weight for that type. The products obtained for all cylinder types are then summed together to give the total SF₆ use.

A3.3.5.3. Methodology—Quantifying Equipment Disposal and Failure Emissions

Equipment disposal and failure emissions include emissions from decommissioning of retired equipment and emissions that result from the rare event of catastrophic equipment failures.

In the decommissioning of retired equipment, SF₆ losses occur as gas is being recovered from the retired equipment. Emissions can be estimated by taking the difference between the nameplate capacity of the equipment and the recovered amount of SF₆.

Equation A3.3–13

$$\begin{aligned} \text{Equipment decommissioning emissions} = \\ \text{Nameplate capacity of retired equipment} - \text{SF}_6 \text{ amount recovered from retired equipment} \end{aligned}$$

The value of nameplate capacity (in mass units) can be obtained from equipment specifications provided by the equipment manufacturer or from sound engineering estimates. The amount of recovered SF₆ gas is weighed.

When equipment failure or damage occurs to the point where it cannot be repaired, it is assumed that the nameplate capacity of the equipment is representative of the emissions that have taken place as a result of equipment failures.

The information provided in this section (5) is extracted from the *SF₆ Emission Estimation and Reporting Protocol for Electric Utilities* (EC and Canadian Electricity Association 2008), available at <http://www.publications.gc.ca/site/eng/454401/publication.html>. For further details on data uncertainty, data quality control, data verification by third party, transfer of information and data to ECCC, documentation and archiving, new information or data updates, and protocol reviews and amendments, please refer to the Protocol.

A3.3.5.4. Data Sources

The SF₆ emissions by province for 2006–2020 were provided by the Canadian Electricity Association and BC Hydro.

A3.4. Methodology for the Agriculture Sector

Overview of Agricultural Emission Methodologies

This section of Annex 3 describes the estimation methodologies, equations, activity data, emission factors and parameters that are used to derive the greenhouse gas (GHG) estimates in the Agriculture sector, namely:

- methane (CH_4) emissions from enteric fermentation
- CH_4 and nitrous oxide (N_2O) emissions from manure management and field burning of agricultural residues
- N_2O emissions from agricultural soils (direct emissions, indirect emissions and animal manure emissions on pasture, range and paddock [PRP])
- carbon dioxide (CO_2) emissions from agricultural use of lime and urea

The sources of animal population data required to calculate agricultural emissions of CH_4 and N_2O are presented in section A3.4.1. The methods used to calculate agricultural GHG emissions are described in sections A3.4.2 to A3.4.8. Note that agricultural soils also emit and sequester CO_2 , but these sources/sinks are reported in the Land Use, Land-Use Change and Forestry (LULUCF) sector (see Annex 3.5).

Livestock and crop production are integrated systems that interact in the production of GHG emissions. The GHG estimation methodology described in Annex 3.4 begins with an estimation of emissions related to livestock production, followed by emissions related to crop production (Figure A3.4–1). All approaches prescribed by Intergovernmental Panel on Climate Change (IPCC, 2006) for calculating emissions follow the basic formula of “activity data” x “emission factor”. In the case of agricultural emissions, “activity data” may refer to the number of animals, an amount of nitrogen (N) applied to soils, or some other measure of agricultural activity. “Emission factor” is an average emission rate for a specific GHG from a given source, relative to a unit of activity data. The calculation of agricultural emissions is often sequential, as many processes are inter-related. For example, changes in livestock populations and characteristics may alter the quantity of manure N that is passed from the livestock system to the cropping system.

Livestock emissions are primarily driven by animal populations, but emission factors are dependent on other drivers. The quality and quantity of animal feed influences how quickly animals grow and how much they produce (e.g. dairy cow milk production) but changes in animal feed characteristics will affect the amount of CH_4 that is produced by an individual animal and how much manure, and therefore both carbon (C) and N, they excrete back into the environment. As a result, feed quality and animal productivity can be drivers that change livestock emission factors over time. Furthermore, changes in manure management infrastructure (for manure storage and spreading), or farming practices such as changes to the amount of time animals spend on pasture, may further alter the quantity or profile of emissions. Therefore, emission factors can also vary from year to year, in addition to activity data.

Livestock estimation methodologies used in the National Inventory Report (NIR) can generally be grouped into four categories: (1) dairy, (2) beef (non-dairy), (3) swine, and (4) all other animals (Figure A3.4–1). For the beef category, emission estimates from the process of enteric fermentation and management of animal manure are based on IPCC Tier 2 methodologies populated with country-specific parameters collected through an expert consultation (Boadi et al., 2004a; Marinier et al., 2004), and animal production data in the form of carcass weight increase (AAFC, n.d. [b]). For the dairy category, the expert consultation was improved by the introduction of better feed data and production data, and the introduction of information derived from Statistics Canada’s farm environmental survey data. For the “swine” and “all other animals” categories, the default IPCC tier 1 methodology is used to estimate emissions from the process of enteric fermentation. Emissions from the management of swine manure are estimated using a Tier 2 methodology based on expert consultation data (Marinier et al., 2004), animal production data in the form of carcass weight increases, and information derived from farm environmental surveys. For most other livestock, emissions from the management of manure emissions are calculated based on expert consultations or IPCC Tier 1 methods. Emissions from animals other than cattle, swine, sheep, poultry, horses and bison represent less than 0.5% of total agricultural emissions and less than 0.05% of total national anthropogenic emissions.

N_2O emissions from crop production on agricultural soils are primarily driven by N fertilizer sales, annual crop areas, the type of N applied and the cropping system to which they are applied. To a lesser extent, emissions within a province are influenced by the availability of manure and biosolids relative to crop N requirements. A combination of activity data (animal populations) and drivers such as feed quality and quantity; animal productivity and manure management infrastructure influence the total quantity of N that is passed from the livestock system to agricultural soils and the amount of N lost to the environment during these transfers.

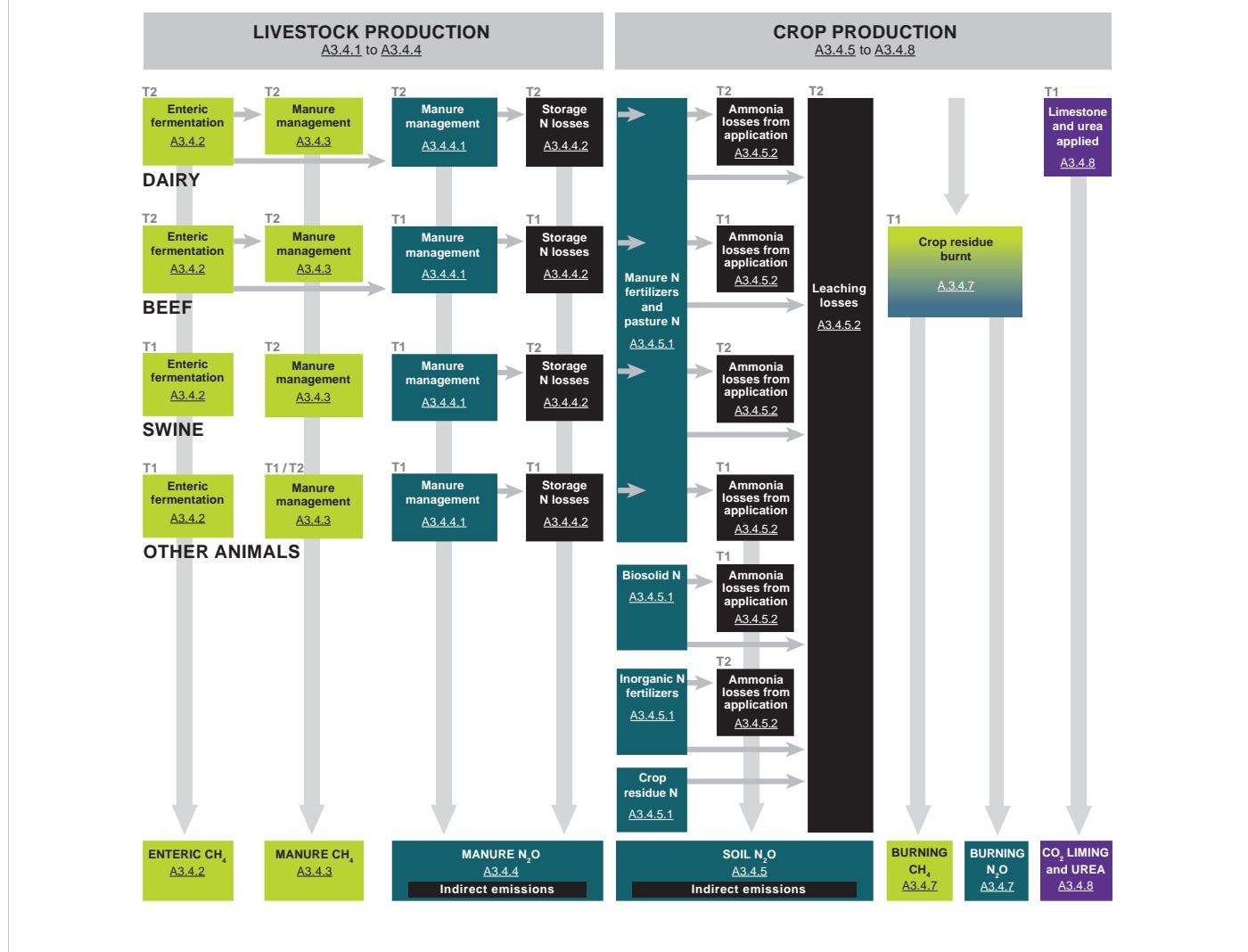
Spatially, N is distributed to agricultural ecodistricts, which represent one level within Canada’s National Ecological Framework. The country is divided into 1027 ecodistricts, characterized by a distinctive assemblage of relief, landforms, geology, soil, vegetation, water bodies and fauna. Application rates are calculated as a function of the total organic N in

the ecodistrict and crop requirements, which are then adjusted to provincial fertilizer sales as outlined in section A3.4.5. A country-specific emission factor for agricultural soils is calculated for each ecodistrict (section A3.4.5.1) that is adjusted based on the source of N, cropping system, topography, soils and climate of the ecodistrict, as well as management practices such as tillage and irrigation. Emissions are then calculated from the amount of N applied to the soil, multiplied by the unique emission factor for the ecodistrict in which it was applied. The quantity of emissions that results from a given unit of N added to soils therefore varies by ecodistrict. Sources of N include inorganic fertilizers, organic fertilizers and crop residue (N contained in plant matter remaining in fields after harvest).

Nitrogen is tracked throughout the process of crop production and ammonia losses after application of fertilizer and manure to croplands are calculated at a Tier 2 level for fertilizer and manure N from dairy and swine (Tier 1 IPCC default loss factors are used for all other animals). Indirect emissions of N_2O from N that is lost from the agriculture system are estimated using Tier 1 IPCC 2006 emission factors (section A3.4.5.2).

Minor emission sources, such as CO_2 emissions from agricultural use of lime and urea and CH_4 and N_2O emissions from field burning of agricultural residues, are described in sections A3.4.8 and A3.4.7, respectively.

Figure A3.4–1 Overview of the Key Methodologies and IPCC Tier Levels Used in Livestock and Crop Production



A3.4.1. Animal Population Data Sources

Annual livestock population data at a provincial level were used to develop emission estimates. Livestock and poultry populations, by animal subcategory and by province, were obtained from Statistics Canada and other sources, as described in Table A3.4–1.

Annual cattle, sheep and swine populations are presented as the simple mean of semi-annual or quarterly surveys. These smaller surveys are corrected by Statistics Canada to the *Census of Agriculture* (COA) population estimates, which are collected every five years, to assure the accuracy of the estimates.

The population estimates for horses, goats, bison,¹⁴ llamas and alpacas, deer and elk, wild boars, rabbits and poultry are taken from the COA exclusively, and annual populations are developed by linear interpolation in order to avoid large changes in census years. Populations of deer and elk, considered new to Canadian livestock production and only reported in the COA for census years beginning in the reporting period, were extrapolated back to zero for the census year previous to their first appearance in the COA. Mule and ass populations were received via personal communication¹⁵ and originate

¹⁴ In the CRF tables, the IPCC animal category Buffalo is used to report values for North American bison (*Bison bison*) raised for meat.

¹⁵ Laborde L. 2015. Personal communication (e-mail from Laborde L to Section Head, Agriculture, Forestry and Other Land Uses, dated September 2, 2015). Pollutant Inventories and Reporting Division, ECCC.

Table A3.4–1 Animal Categories and Sources of Population Data

Category	Sources/Notes
Cattle	Statistics Canada. Note date. Table: 32-10-0130-01 (formerly: CANSIM 003-0032)—Number of cattle, by class and farm type, annual (head) [accessed October 20, 2021]. Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210013001 .
– Dairy Cattle	All cattle used in the production of milk and milk products
– Non-dairy Cattle	All other cattle
Bison, Goats, Horses, Llamas and Alpacas, Deer and Elk	Statistics Canada. 2008. Alternative Livestock on Canadian Farms: Census years 1981, 1986, 1991, 1996, 2001 and 2006 (Catalogue No. 23-502-X), 2011 and 2016 <i>Census of Agriculture</i> : Statistics Canada. Table: 32-10-0427-01 (formerly CANSIM 004-0224). Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042701 - linear interpolation between census years, remains constant after last census
Wild Boars	Census year 2016 a: Taylor, Patrick (Statistics Canada). Personal communication received September 21, 2018. Census years 2001 to 2011: Statistics Canada. 2008. Alternative Livestock on Canadian Farms: Census years 1981, 1986, 1991, 1996, 2001 and 2006 (Catalogue No. 23-502-X), 2011 Census: Statistics Canada. Table 95-640-XWE - 2011 Farm and farm operator data (database). Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042701 - linear interpolation between census years, remains constant after last census Census years a 1991, 1996: Laborde, Leon (Statistics Canada). Personal communication received October 26, 2016. - linear interpolation between census years, 1990 kept constant from 1991
Mink and Foxes	Statistics Canada. No date. Table 32-10-0116-01 (formerly CANSIM Table 003-0015) - Supply and disposition of mink and fox on fur farms, annual (Number) [accessed October 28, 2021]. Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210011601 .
Mules and Asses ^a	Census year 2016: Laborde L (Statistics Canada). Personal communication received May 16, 2018. Census years 2001 to 2011: Laborde L (Statistics Canada). Personal communication received September 2, 2015. - population held constant prior to 2001 census, and after the last census
Rabbits	Agriculture and Agri-Food Canada, Red Meat Market Information, Alternative Livestock. Available online at: https://agriculture.canada.ca/%20eng/animal-industry/red-meat-and-livestock-market-information/rabbit-industry-at-a-glance/?id=1415860000120 - linear interpolation between census years, remains constant after last census - correction factor applied to isolate the breeding population based on expert opinion from Brian Tapscott, Alternative Livestock Specialist, OMAFRA
Sheep and Lambs	Statistics Canada. No date. Table 32-10-0129-01 (formerly CANSIM 003-0031)—Number of sheep and lambs on farms, annual (head) [accessed October 26, 2021]. Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210012901 .
Swine	Statistics Canada. No date. Table 32-10-0290-01 (formerly CANSIM 003-0004)—Number of hogs on farms at end of quarter, quarterly (head), CANSIM (database). Years 1990–2006. Statistics Canada. Table 32-10-0145-01 (formerly CANSIM 003-0100)—Hogs statistics, number of hogs on farms at end of semi-annual period, (head). Years 2007–2018 [accessed October 26, 2021]. Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210014501 .
Poultry	Farm data and farm operator data tables (section 6.5 of publication #95-629) (Statistics Canada [2007a]) Selected historical data from the <i>Census of Agriculture</i> , Canada and provinces: census years 1976 to 2006 (Table 2.16 and section 4.6 of Statistics Canada Catalogue No. 95-632). (Statistics Canada [2007b]) 2011 and 2016 Census: Statistics Canada. Table: 32-10-0428-01 (formerly CANSIM 004-0225). Poultry inventory on census day [accessed October 22, 2018]. Available online at: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210042801 - linear interpolation between census years and remains constant after latest census

Note:

a. These data may be affected by errors due to coverage.

from recently compiled responses to the COA for the years 2001, 2006 and 2011. Mule and ass populations were not compiled prior to the 2001 census year and were assumed to be constant at the 2001 level from 1990 to 2000. Wild boar populations for census years 1991, 1996 and 2016 were received via personal communication^{16, 17} and were compiled from responses to the COA. Wild boar and buffalo populations were not collected in 1986; thus, the populations were set constant for 1990 at the 1991 level.

The estimates for breeding mink and fox populations are taken from an annual Statistics Canada survey titled *Supply and Disposition of Mink and Fox on Fur Farms*, which provides the number of foxes and mink on farms for January 1 of the survey year. Rabbit populations were taken from responses to the COA as provided on the Agriculture and Agri-Food Canada (AAFC) Red Meat Market website (AAFC, n.d. [a]), but were modified based on expert opinion¹⁸ using a correction factor in order to estimate the number of does, as opposed to total rabbits.

To populate an IPCC Tier 2 enteric fermentation approach for the Beef and Dairy sectors, the subcategories of provincial cattle populations collected by Statistics Canada were further disaggregated into subannual production stages (i.e., “production subcategory”) to isolate and quantify the effect of specific production practices on gross energy (GE) intake and, as a consequence, CH₄ emissions. Data to describe the production environment and associated performance of classes of animals were collected from a combination of sources, including: (1) production and management practices published in scientific journals; (2) a survey of dairy and beef production practices conducted and administered to regional and provincial beef and dairy livestock specialists across the country; (3) consultation with scientists at universities and federal research institutions; and (4) provincial/national associations and provincial/regional performance-recording organizations (Boadi et al., 2004a).

These data were used to create an annual cattle production approach that takes into account regional and seasonal variations in production practices. The eight cattle subcategories were broken down into 38 distinct cattle production stages—29 for the Beef sector and 9 for the Dairy sector—observed throughout the different provinces of Canada (Table A3.4–2). The approach characterizes cattle by physiological status, diet, age, sex, weight, growth rate, activity level and production environment. Further work on the Dairy sector was implemented in the 2018 inventory analysis to refine estimates of certain Tier 2 parameters. This update created a time series datum that better captures changes in production practices in the Dairy sector and introduced an analysis of changes in dairy nutrition considering more recent Canadian and North American research (Ellis et al., 2007; Ellis et al., 2010; Sheppard et al., 2011a, 2011b; Vanderzaag et al., 2013; Appuhamy et al., 2016; Chai et al., 2016; Jayasundara et al., 2016).

The feeding practices for Beef and Dairy sector livestock are detailed in the next section.

Dairy Sector Production and Performance

Dairy production practices vary across the country because of differences in land prices, climate, forage availability and market access. They have also changed significantly between 1990 and the present. The predominant management practices for each province are reflected in the province-specific parameters entered into the IPCC Tier 2 equations for both enteric fermentation and manure management emissions.

Table A3.4–3 provides an example of production performance data collected for the Canadian Dairy sector, originally used as a quality assurance verification of the data incorporated in the Tier 2 method at the inception of the Boadi et al. (2004a) study. While the basic subcategory classes developed by Boadi et al. (2004a) were accurate for the mid-2000s when the Tier 2 model was populated, it was recognized that certain production parameters were not static over time and that these parameters could impact all aspects of emissions from the sector. Since 1990, with the increase in milk production in the dairy herd, there has also been a shift in the diet of an average dairy cow, both in the quantity and quality of feed consumed.

There are no consistent national data sources for complete dairy feed quality linked to dairy production and performance. However, certain regional and partial resources exist, specifically the feed quality database from Lactanet¹⁹ for parts of Eastern Canada and Cost of Production²⁰ (COP) surveys for Quebec and Ontario. However, consistent milk production statistics do exist for the entire country. Production statistics identifying the relative proportions of the national dairy herd that fall into high, medium and low productivity classes and are linked to herd characteristics such as farm size are collected, managed and prepared for the inventory by Lactanet.

¹⁶ Laborde L. 2016. Personal communication (e-mail from Laborde L to Flemming C, Agriculture, Forestry and Other Land Uses, dated October 26, 2016). Pollutant Inventories and Reporting Division, ECCC.

¹⁷ Taylor, P. 2016. Personal communication (e-mail from Taylor P to Flemming C, Agriculture, Forestry and Other Land Use, dated September 21, 2018).

¹⁸ Tapscott B. 2015. Personal communication (e-mail from Tapscott B, OMAFRA, to Section Head, Agriculture, Forestry and Other Land Uses, dated September 16, 2015). Pollutant Inventories and Reporting Division, ECCC.

¹⁹ <https://lactanet.ca/en/library/>

²⁰ cdc-ccl.gc.ca/CDC/index-eng.php?id=3941

Table A3.4-2 Cattle Production Stage Approach

Subcategory	Production Environment	Period of Year ^a	Province
Beef cows	Pregnant, confined	Jan–Apr/Oct–Dec	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Beef cows	Lactating, pasture	May–Oct	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Beef cows	Pregnant, confined	Feb–Mar	MB
Beef cows	Lactating, pasture	Jan/Mar–Dec	MB
Breeding bulls	Mature, confined	Jan–Apr/Nov–Dec	PE/NS/QC/ON/MB/SK/AB/BC
Breeding bulls	Mature pasture	May–Oct	PE/NS/QC/ON/MB/SK/AB/BC
Breeding bulls	Young confined	Mar–Apr	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Breeding bulls	Young pasture	May–Oct	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Breeding bulls	Young confined	Nov–Dec/Jan–Feb	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Beef calves	Birth to pasture	Mar	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Beef calves	Pasture	Apr–Sep	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Beef calves	Heifer replacement	Oct–Dec/Jan–Mar	PE/NS/QC/ON/MB/SK/AB/BC
Beef calves	Background heifers	Oct–Dec/Jan–Mar	PE/NS/QC/ON/MB/SK/AB/BC
Beef calves	Background steers	Oct–Dec/Jan–Mar	NL/PE/NS/NB/ON/MB/SK/AB/BC
Beef calves	Finisher heifers	Oct–Dec/Jan–Mar	NL/PE/NS/NB/ON/MB/SK/AB/BC
Beef calves	Finisher steers	Oct–Dec/Jan–Mar	PE/NS/NB/ON/MB/SK/AB/BC
Heifer replacement	Young, not pregnant	Apr–May	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Heifer replacement	Early gestation	Jun–Sep	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Heifer replacement	Late gestation	Oct–Dec/Jan–Mar	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Finisher heifers	Feedlot, short-keeps	Apr–Jun	PE/NS/NB/ON/MB/SK/AB/BC
Finisher steers	Feedlot, short-keeps	Apr–Jun	PE/NS/NB/ON/MB/SK/AB/BC
Finisher heifers	Feedlot short-keep long-finish	April–Jul	NS/ON/MB
Finisher steers	Feedlot short-keep long-finish	April–Jul	NS/ON/MB
Background heifers	Confined	Mar–May	NL/NS/ON/MB/SK/AB/BC
Background steers	Confined	Mar–May	NL/NS/ON/MB/SK/AB/BC
Background heifers	Pasture	Jun–Sep	NL/NS/ON/MB/AB/BC
Background steers	Pasture	Jun–Sep	NL/NS/ON/MB/AB/BC
Finisher heifers	Feedlot, long-keeps	Oct–Dec	PE/NS/NB/QC/ON/MB/SK/AB/BC
Finisher steers	Feedlot, long-keeps	Oct–Dec	PE/NS/NB/QC/ON/MB/SK/AB/BC
Dairy cows	Lactating, confined	var ^b	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Dairy cows	Lactating, pasture	var	NL/PE/NB
Dairy cows	Lactating, confined (after pasture)	var	PE
Dairy cows	Dry, low-quality feed	var	NL/PE/NS/NB/QC/ON/MB/SK/BC
Dairy cows	Dry, high-quality feed	var	MB/SK/AB/BC
Dairy cows	Dry, pasture	var	NL/ON
Dairy heifers	Confined (243 days per year)	Jan–Apr/Oct–Dec	NL/PE/NS/NB/QC/ON/MB/SK/AB/BC
Dairy heifers	Pasture	May–Oct	NL/PE/NB/ON/SK
Dairy heifers	Confined (365 days per year)	Jan–Dec	NB/ON/SK

Notes:

a. Actual period of the year could vary slightly from province to province.

b. Variable dependent on farm, province and animal cycles.

To develop parameters that link productivity with production practice, the feed quality database developed by Lactanet, consisting of feed data collected and analyzed for more than 2000 dairy herds in Quebec and Atlantic Canada, was used as a model to develop a matrix of animal diets that could be related to specific farm sizes and productivity classes. Feed composition, digestibility, crude protein content and some herd characteristics, such as lactation lengths and cattle weights, were grouped according to five categories of farm size and three categories of productivity class. The feed composition statistics required for Tier 2 calculations were attributed to provinces based on the proportions of their animal populations that fell into different farm size and productivity classes. As the data used in this analysis from Lactanet were collected between 2000 and 2010, further COP survey data were used as a proxy to project changes in certain feed components, specifically the proportion of silage in diets relative to the proportion of hay for the period of 1990 to 1999.

Table A3.4-3 Typical Characteristics of Dairy Production in 2001 in Canada

Animal Category/Parameters	Production Characteristics ^b	Data Sources ^c
Dairy cows^a		
Average weight, kg	634 (51)	Okine and Mathison (1991); Kononoff et al. (2000); Petit et al. (2001)
Mature weight, kg	646 (55)	
Conception rate, %	59.2 (7.3)	
Calves		
Birth weight, kg	41 (3.3)	
Average weight, kg	186 (18.5)	
Mature weight, kg	330.5 (37.6)	
Daily weight gain, kg day ⁻¹	0.7 (0.3)	
Calf crop, ^d %	93 (6)	
Replacement heifers		
Average weight, kg	461.6 (24.7)	
Beginning weight (1 year), kg	327.8 (31.0)	
Mature weight at calving, kg	602.1 (45.9)	
Mature weight, kg	646.1 (54.9)	
Daily weight gain, kg day ⁻¹	0.77 (0.14)	
Replacement rate, %	32.3 (3.2)	Western Canadian Dairy Herd Improvement Services (2002)
Notes:		
a. Values represent typical values observed in Canada but not population-weighted averages quantitatively representing Canadian dairy production, as reported in the CRF.		
b. The numbers in parentheses are the standard deviation.		
c. Values with no reference were obtained from expert consultations (see Boadi et al., 2004b).		
d. "Calf crop" is the percentage of the overwintering cows that produced a live calf.		

A time series consisting of the annual weighted provincial averages for feed digestibility, lactation lengths and crude protein content in feed was transferred into the existing structure for the Boadi et al. (2004) approach. Furthermore, provincial cattle weights for dairy animals were modified based on average measurements included in the Lactanet database for each farm size and productivity class. The percentage change in cattle weight was used as an indicator of changes in body weight, mature weight and weight gain from the 2001 benchmark values established by Boadi et al. (2004a). The resulting dairy animal weight time series is also incorporated into the Tier 2 methodology.

Milk Yield and Fat Data

Milk productivity has increased in all Canadian provinces (Table A3.4-4), as documented by Lactanet,²¹ which collects a sample of milk production representing more than two-thirds of the Canadian dairy cow population for the 1999–2019 period and compiles and prepares the data for use in the inventory. These data represent the best estimate of actual milk production per average cow per province in Canada. However, from 1990 to 1998, this data set does not exist for all of Canada. The only data that are available from 1990 to 1998 for all of Canada are publishable data that were reported by AAFC. The publishable data are collected for the most productive animals and the quantity of milk that is produced in the first 305 days of their lactation period. The time series of real milk production for the entire Canadian herd from 1990 to 1998 was calculated based on the average ratio between the publishable data and the management data from 1999 to 2007. The trend of increased milk production is reflected in the emission factor for dairy cows.

Duration of Time in a Production Environment

It was assumed that cows that were dry (not lactating) during the summer months were on pasture; cows that were dry during the remainder of the year were in confinement. Replacement heifers were assumed to calve at 24 months. Lactation cycles were on average 320 days; however, cycles vary regionally and are based on herd productivity.

Percentage of Cows Pregnant

An estimate of the percentage of cows pregnant in the herd at any given time was calculated in Boadi et al. (2004a) by dividing average gestation length by the regional average calving interval and subtracting the number of cows that are culled annually due to reproductive failure.

²¹ <https://lactanet.ca/en/library/>

Table A3.4–4 Average Milk Production from 1990 to 2020 at a Provincial Level

Year	Average Milk Production (kg head ⁻¹ day ⁻¹)										
	NL	PE	NS	NB	QC	ON	MB	SK	AB	BC	
1990	21.0	20.9	21.0	20.8	20.3	21.7	22.1	22.2	23.2	24.3	
1995	23.1	23.1	23.2	23.0	22.2	24.0	24.2	24.2	25.5	26.8	
2000	27.4	26.1	26.8	26.4	25.5	26.5	27.9	27.7	29.0	30.0	
2005	27.0	27.1	26.9	26.4	25.9	26.7	27.4	29.3	29.3	30.4	
2010	27.4	27.8	27.7	26.8	27.3	27.8	28.8	31.1	30.6	31.1	
2011	27.9	28.5	28.3	27.0	27.4	28.0	28.3	30.1	30.2	30.7	
2012	27.9	28.5	27.9	27.1	27.4	28.4	28.4	30.6	30.9	30.4	
2013	29.6	29.7	29.1	28.5	28.7	30.2	30.7	32.0	32.8	32.7	
2014	30.0	29.3	28.4	27.6	28.8	29.5	29.8	32.9	33.0	32.6	
2015	30.3	29.4	28.9	27.3	28.7	30.1	30.6	33.1	34.2	33.0	
2016	30.9	30.0	29.7	27.6	29.3	31.0	31.5	35.6	35.5	34.0	
2017	30.5	31.3	30.8	28.4	29.8	31.3	31.5	35.0	34.6	32.2	
2018	31.8	31.6	31.1	29.8	30.3	31.3	32.0	37.0	35.5	33.9	
2019	34.9	33.1	32.0	30.2	31.2	32.5	33.2	36.4	35.7	34.3	
2020	33.7	32.8	31.6	30.4	31.5	33.2	34.1	36.2	34.7	35.1	

Note:

Data source = Lactanet (2020)

Ration Digestibility (DE%)

Digestibility of rations (DE%) was based on feed data in the Lactanet database and cost of production surveys. The values used in the Tier 2 calculations are weighted averages based on measured digestibility in the different diets associated with a specific farm size and productivity class from the data collected by Lactanet. For individual provinces not represented directly by Lactanet's data, DE% values were obtained by multiplying the DE% by the proportion of animals in each farm size and productivity class for each province. The provincial DE% time series was then inserted into the existing Tier 2 approach, replacing the fixed values from Boadi et al. (2004a).

Since 1990, the proportion of hay in feed has decreased, while the proportion of silages has increased. Silages typically have a higher feed value as the digestible portion of the feed is better preserved and, as a result, more of the feed is available for digestion by the animal. Furthermore, there has been a small overall increase in the amount of concentrates and supplements used in diets. Overall, DE% ranges from 69% to 72% for lactating cows, and 63% to 65% for dry cows, while heifers were assumed to have a diet similar to dry cows.

A3.4.1.1. Non-Dairy Cattle

Production Practices and Performance

Production practices for livestock reported under Non-Dairy Cattle also vary across the country due to climate, land prices and differences in traditional farming practices. The study conducted by Boadi et al. (2004a) characterized the predominant practices in 2001 for each province according to animal type, physiological status, age, gender, growth rate, activity level and production environment. The values presented in Table A3.4–5 provide examples of production performance data collected for Canadian beef cattle, originally used as a QA verification of the data incorporated in the Tier 2 method.

Trends in carcass weights are used as an indicator of changes in mature weight from the 2001 benchmark values established by Boadi et al. (2004a) for the specific animal subcategories presented in Table A3.4–6. Carcass weight data are collected by the Canadian Beef Grading Agency (CBGA) and published by AAFC (AAFC, n.d. [b]). Carcass weights increased from 1990 to 2003 for beef cows, heifers for slaughter, steers and bulls (Figure A3.4–2). Since 2003, beef cow carcass weights have remained more or less stable, but slaughter animal weights have continued to increase until recently when weights stabilized. In 2003, the Canadian beef cattle industry was affected by bovine spongiform encephalopathy disease, which shut down beef exports to the United States. After 2003, the slaughtered carcass weights of bulls had evidently increased due to the culling of older bulls. To provide an estimate more representative of the on-farm herd, the average live weights of bulls were retained at their 2002 value. From 2009 to 2018, the slaughter weights of bulls were used in the time series again. Bull weights were observed to decrease considerably in 2013. This observation was verified; in general, bull weights are prone to higher variability due to the low numbers being slaughtered on an annual basis.

Table A3.4-5 Typical Characteristics of Beef Production in Canada in 2001 from Various Sources

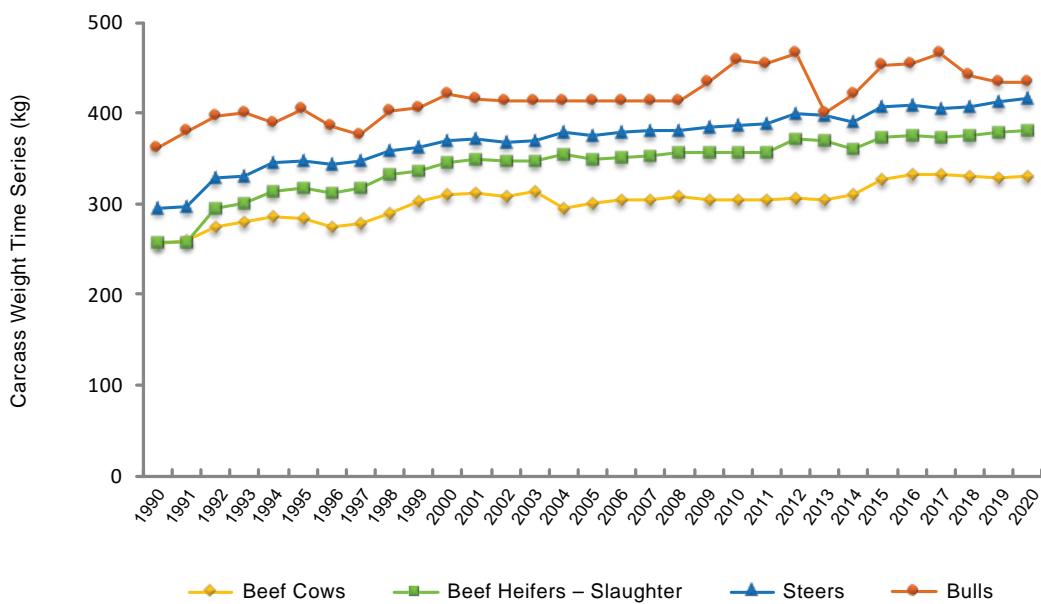
Animal Category/Parameters	Production Characteristics ^a	Data Sources ^b
Beef Cows		
Average weight, kg	603 (36)	Kopp et al. (2004)
Mature weight, kg	619 (52)	AAFRD (2001)
Milk, kg day ⁻¹	7.3 (1.2)	Kopp et al. (2004)
Milk fat, %	3.6 (0.6)	Kopp et al. (2004)
Conception rate, %	93.7 (1.3)	Manitoba Agriculture and Food (2000); AAFRD (2001)
Replacement Heifers		
Average weight, kg	478 (34)	
Mature weight, kg	620 (51)	
Daily weight gain, kg day ⁻¹	0.64 (0.14)	
Replacement rate, %	14.4 (3.1)	Manitoba Agriculture and Food (2000)
Bulls		
Yearling weight, kg	541 (18)	
Average weight, kg	940 (98)	
Mature weight, kg	951 (112)	
Daily weight gain, kg day ⁻¹	1.0 (0.17)	
Calves (including Dairy Calves)		
Birth weight, kg	40 (3)	AAFRD (2001)
Wean weight, kg	258.4 (19.1)	Small and McCaughey (1999)
Age at weaning, days	215 (15)	
Daily Weight Gain, kg day⁻¹		
- Replacement heifers	0.67 (0.13)	Kopp et al. (2004)
- Backgrounder	0.98 (0.17)	
- Finisher	1.37 (0.12)	
Calf crop, %	95 (2.3)	
Heifer and Steer Stockers		
Average weight, kg	411 (47)	Kopp et al. (2004)
Mature weight, kg	620 (51)	
Daily weight gain, kg day ⁻¹	0.98 (0.16)	
Proportion to feedlot, %	65 (30)	
Feedlot Animals		
Average weight, kg		
- Direct finish	540 (25)	
- Background finish	562 (64)	
Mature weight, kg	630 (46)	
Finish weight, kg	609 (28)	
Daily weight gain, kg day ⁻¹	1.37 (0.12)	
Notes:		
Values represent typical values observed in Canada but not population-weighted averages quantitatively representing Canadian beef production, as reported in the CRF.		
a. The numbers in parentheses are the standard deviations.		
b. Values with no reference were obtained from expert consultations compiled in Boadi et al. (2004b).		

Duration of Time in a Production Environment

Replacement heifers over 15 months of age are assumed to be bred or pregnant. All replacement stock (breeding bulls, young and replacement heifers over 12 months of age) is assumed to enter the breeding herd (mature breeding bulls and beef cows) at 24 months of age. Slaughter heifers and steers at 12 months of age are either in feedlots or backgrounded. Animals scheduled for slaughter may be identified as either short-keeps or long-keeps. Short-keeps go directly to the feedlot to be slaughtered after 3 to 4 months, whereas long-keeps are typically backgrounded for 6 months before being sent to feedlots, where they are finished after 2 to 4 months.

Figure A3.4-2 Non-Dairy Cattle Carcass Weight, Based on Data Collected by CBGA and Published by Agriculture and Agri-Food Canada

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Ration Digestibility (DE%)

Forage DE% values determined by Christensen et al. (1977) for forages grown on the Prairies were used to estimate DE% for Saskatchewan and Manitoba. Values from Alberta Agriculture, Food and Rural Development and the University of Alberta (2003) were used for Alberta, whereas values from the U.S. National Research Council (2001) were used to estimate DE% for British Columbia and the Eastern provinces. Overall, DE% ranged from 60% to 84%, depending on rations and feeding regimes.

Calves were assumed to have a non-functional rumen or to consume very small amounts of dry feed from birth until two or three months of age. Therefore, enteric CH₄ emissions in these first few months are assumed to be zero.

Examples of Regional Variability and Disaggregation of Parameters

The country-specific methodologies used by Canada to estimate emissions from Cattle are carried out at various spatial and categorical scales, and are weighted to the national and Common Reporting Format (CRF) category levels for reporting in the NIR and in the CRF.

Due to the variability in parameters across the country, as a result of farming practices, livestock populations, climate, cropping systems, soil characteristics, and other factors, Canada's national estimates presented in the CRF represent weighted average data. Many of the calculations are carried out at a highly disaggregated level. Data are processed through a series of relational databases, and with tables that may contain more than 10 million records. This section aims to present some examples of cattle parameters for select year(s), region(s) and livestock categories, to improve transparency around the country-specific approaches for cattle. An example of the provincial livestock activity data obtained from Statistics Canada is provided in Table A3.4-7, for major livestock types and for the most recent inventory year.

For the calculation of emissions from enteric fermentation from cattle, populations are maintained at the provincial spatial scale; however, the eight cattle subcategories are disaggregated into 38 production subcategories listed in Table A3.4-2 and following the approach in section A3.4.2. The calculation of GE is carried out as described in Equation A3.4-2 for each production subcategory (Table A3.4-8). The GE for each production subcategory is then weighted by the amount of time spent in each stage of production, to arrive at a weighted GE per livestock subcategory and converted to dry matter intake (DMI) as shown in Table A3.4-10 during the calculation of the emission factor in Equation A3.4-4. The provincial emission factors, provincial GE, provincial milk production (Table A3.4-4), provincial cattle weights (Table A3.4-9) and other parameters are weighted by the fraction of provincial subcategory populations to national category populations and summed to arrive at the national values reported in the CRF tables for "Dairy Cattle" and "Non-Dairy Cattle".

Table A3.4–6 Indicators of Live Body Weight Change Over Time for Cattle Subcategories

Cattle Subcategory	Trend in Live Weight Applied
Beef cows	Trends in beef cow carcass weight used as an indicator of live weight.
Heifers for slaughter	Trends in heifer carcass weight used as an indicator of live weight.
Beef heifers	Trends in beef cow carcass weight used as an indicator of live weight.
Steers	Trends in steer carcass weight used as an indicator of live weight.
Bulls	Trends in bull carcass weight used as an indicator of live weight from 1990 to 2002; 2003 to 2008 live weights are set constant to the 2002 live weight; 2009–Present uses carcass weight trend again.
Calves	No change
Dairy cows	Provincial trends in dairy cow productivity are used along with average body weight by productivity class as an indicator of live weight.
Dairy heifers	Trends in dairy cow live weight used as an indicator of dairy heifer live weight.

Table A3.4–7 Provincial Livestock Population Activity Data by Subcategory for Select Livestock in 2020

Category	Subcategory	Population (x1000 head)									
		AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
Cattle	Dairy Cows	82	85	37	19	5.9	21	321	14	361	29
	Beef Cows	1 451	207	402	12	0.4	16	246	9.6	144	1 092
	Bulls	85	13	22	0.6	0.1	1.3	18	0.7	8.9	59
	Dairy Heifers	41	43	22	8.3	2.2	9.0	152	6.4	145	10
	Beef Heifers	232	39	66	1.9	0.2	2.6	42	1.3	18	174
	Heifers for Slaughter	505	24	39	2.1	0.2	2.4	126	5.6	31	73
	Steers	728	27	61	3.6	0.3	3.3	265	7.9	65	136
	Calves	1 623	206	375	16	2.3	20	412	15	357	839
Sheep & Lamb	Sheep	94	25	36	3.5	1.1	9.5	174	3.8	124	50
	Lamb	69	18	49	2.5	1.2	6.5	114	4.9	79	45
Swine	Sows	130	8.0	345	8.4	0.1	3.5	314	4.0	312	103
	Boar	4.9	0.3	3.0	0.1	0.0	0.1	4.2	0.1	2.0	2.1
	Pigs (<20 kg)	545	34	1 382	18	0.5	11	1 391	16	1 462	373
	Pigs (20–60 kg)	320	21	667	1.4	2.4	21	805	7.6	983	192
	Pigs (>60 kg)	541	23	958	2.7	0.7	15	1 132	12	1 560	300
Poultry	Turkeys	769	862	775	93	0.2	242	3 772	3.3	1 653	254
	Hens	2 212	3 013	2 715	489	343	810	9 320	147	4 156	1 087
	Pullets	1 095	1 129	1 118	230	44	302	5 328	17	2 002	431
	Broilers	10 819	16 479	4 393	2 125	1 503	3 564	36 112	385	29 828	4 325
Other	Goat	28	15	7.3	1.0	0.1	1.7	130	0.3	36	12
	Buffalo	55	6.5	14	0.0	0.0	0.0	1.8	0.0	1.5	40
	Horses	109	33	21	1.5	0.1	2.1	65	0.9	20	40
	Llamas and Alpacas	5.8	2.5	0.9	0.1	0.0	0.2	5.7	0.2	2.7	2.8

Note:
Source = See Table A3.4–1

For the calculation of N₂O emissions from cattle manure, the eight cattle subcategories in Table A3.4–7 are maintained; however, the spatial scale of the activity data is expanded from 10 provinces to include 405 individual “ecodistricts”, which are further divided into 22 manure management types per animal category to estimate manure management N₂O emissions. The N from manure storage is applied across 32 crop types, in coordination with other N sources, and associated with eight soil N₂O emission factors per ecodistrict to develop the estimate of direct N₂O emissions from land application of manure.

Table A3.4-8 Example of Gross Energy Equation Parameters by Production System, for Two Provinces in 2020

Year	Province	Subcategory	Production Subcategory	NEm	NEa	NEg	NEL	NEp	REM	REG	DE	GE
2020	AB	Dairy Cow	Lactating, confined	47	0	5.5	108	2.8	0.5	0.3	71	439
			Lactating, pasture	0	0	0	108	0	0	0	0	0
			Lactating, confined (after pasture)	0	0	0	108	0	0	0	0	0
			Dry, low-quality feed	0	0	0	0	0	0	0	0	0
			Dry, high-quality feed	39	0	5.5	0	2.3	0.5	0.3	65	154
			Dry, pasture	0	0	0	0	0	0	0	0	0
		Beef Cow	Pregnant, confined	56	0	5.7	0	5.3	0.5	0.3	58	254
			Lactating, pasture	50	18	5.7	23	4.7	0.5	0.3	60	353
			Pregnant, confined	0	0	0	0	0	0	0	0	0
			Lactating, pasture	0	0	0	23	0	0	0	0	0
		Bull	Mature, confined	80	0	0	0	0	0.5	0.3	58	284
			Mature pasture	63	23	0	0	0	0.5	0.3	60	290
			Young confined	54	0	13	0	0	0.5	0.3	58	274
			Young pasture	50	18	14	0	0	0.5	0.3	60	316
			Young confined	79	0	17	0	0	0.5	0.3	58	390
		Dairy heifer	Confined (243 days year)	30	0	15	0	1.8	0.5	0.3	65	174
			Pasture	0	0	0	0	0	0	0	0	0
			Confined (365 days year)	0	0	0	0	0	0	0	0	0
		Beef Heifers	Young, not pregnant	30	0	12	0	0	0.5	0.3	65	150
			Early gestation	33	12	14	0	3.1	0.5	0.3	65	212
			Late gestation	52	0	16	0	5	0.5	0.3	65	251
		Heifers for Slaughter	Feedlot, short-keeps	40	0	40	0	0	0.6	0.4	80	227
			Feedlot short-keep long-finish	0	0	0	0	0	0	0	0	0
			Confined	31	0	13	0	0	0.5	0.3	65	155
			Pasture	35	6	22	0	0	0.5	0.3	65	231
			Feedlot, long-keeps	56	0	42	0	0	0.6	0.4	80	269
		Steer	Feedlot, short-keeps	41	0	34	0	0	0.6	0.4	80	208
			Feedlot short-keep long-finish	0	0	0	0	0	0	0	0	0
			Confined	31	0	11	0	0	0.5	0.3	65	147
			Pasture	36	6.1	18	0	0	0.5	0.3	65	217
			Feedlot, long-keeps	57	0	35	0	0	0.6	0.4	80	249
		Calf	Birth to pasture	8.0	0	3.3	0	0	0	0	0	0
			Pasture	14	5.1	7.9	0	0	0.5	0.3	60	113
			Heifer replacement	33	0	10	0	0	0.5	0.3	65	150
			Background heifers	33	0	11	0	0	0.5	0.3	65	152
			Background steers	33	0	9.1	0	0	0.5	0.3	65	144
			Finisher heifers	38	0	30	0	0	0.6	0.4	80	188
			Finisher steers	38	0	25	0	0	0.6	0.4	80	172
ON	ON	Dairy Cow	Lactating, confined	50	0	8.0	102	2.9	0.5	0.3	71	445
			Lactating, pasture	0	0	0	102	0	0	0	0	0
			Lactating, confined (after pasture)	0	0	0	102	0	0	0	0	0
			Dry, low-quality feed	42	0	8.0	0	2.4	0.5	0.3	62	185
			Dry, high-quality feed	0	0	0	0	0	0	0	0	0
			Dry, pasture	42	7.1	8.0	0	2.4	0.5	0.3	66	187
		Beef Cow	Pregnant, confined	48	0	11	0	4.4	0.5	0.2	56	275
			Lactating, pasture	52	8.9	11	29	4.8	0.5	0.3	65	339
			Pregnant, confined	0	0	0	0	0	0	0	0	0
			Lactating, pasture	0	0	0	29	0	0	0	0	0
		Bull	Mature, confined	69	0	0	0	0	0.5	0.2	56	258
			Mature pasture	63	11	0	0	0	0.5	0.3	65	222
			Young confined	47	0	14	0	0	0.5	0.2	56	274
			Young pasture	50	8.5	16	0	0	0.5	0.3	65	252
			Young confined	64	0	18	0	0	0.5	0.2	56	370
		Dairy heifer	Confined (243 days year)	34	0	15	0	2	0.5	0.3	63	195
			Pasture	34	0	15	0	2	0.5	0.3	68	170
			Confined (365 days year)	34	0	15	0	2	0.5	0.3	63	195
		Beef Heifers	Young, not pregnant	34	0	15	0	0	0.5	0.3	61	198
			Early gestation	36	6.1	17	0	3.3	0.5	0.3	65	221
			Late gestation	47	0	20	0	4.3	0.5	0.3	61	284
		Heifers for Slaughter	Feedlot, short-keeps	40	0	33	0	0	0.6	0.4	84	189
			Feedlot short-keep long-finish	39	0	32	0	0	0.6	0.4	84	186
			Confined	39	0	24	0	0	0.5	0.3	65	234
			Pasture	40	6.8	27	0	0	0.5	0.3	65	275
			Feedlot, long-keeps	45	0	37	0	0	0.6	0.4	84	214
		Steer	Feedlot, short-keeps	41	0	28	0	0	0.6	0.4	84	175
			Feedlot short-keep long-finish	40	0	27	0	0	0.6	0.4	84	172
			Confined	39	0	20	0	0	0.5	0.3	65	217
			Pasture	41	7	23	0	0	0.5	0.3	65	257
			Feedlot, long-keeps	48	0	31	0	0	0.6	0.4	84	202
		Calf	Birth to pasture	9	0	5.0	0	0	0	0	0	0
			Pasture	17	2.8	10	0	0	0.5	0.3	65	109
			Heifer replacement	29	0	13	0	0	0.5	0.3	61	172
			Background heifers	30	0	19	0	0	0.5	0.3	65	185
			Background steers	30	0	16	0	0	0.5	0.3	65	170
			Finisher heifers	31	0	24	0	0	0.6	0.4	84	143
			Finisher steers	31	0	21	0	0	0.6	0.4	84	131

Table A3.4–9 Example of the Cattle Weight Time Series by Production System, for Two Provinces in Select Years

Province	Subcategory	Production Stage	Body Weight (kg)			Mature Weight (kg)		
			1990	2005	2020	1990	2005	2020
AB	Dairy Cow	Lactating, confined	605	608	605	636	639	636
		Lactating, pasture	0	0	0	0	0	0
		Lactating, confined (after pasture)	0	0	0	0	0	0
		Dry, low-quality feed	0	0	0	0	0	0
		Dry, high-quality feed	605	608	605	636	639	636
		Dry, pasture	0	0	0	0	0	0
	Beef Cow	Pregnant, confined	503	590	649	503	590	649
		Lactating, pasture	503	590	649	503	590	649
		Pregnant, confined	0	0	0	0	0	0
		Lactating, pasture	0	0	0	0	0	0
	Bull	Mature, confined	790	906	950	790	906	950
		Mature pasture	790	906	950	790	906	950
		Young confined	479	550	576	790	906	950
		Young pasture	580	666	698	790	906	950
		Young confined	706	810	849	790	906	950
	Dairy heifer	Confined (243 days year)	429	431	429	636	639	636
		Pasture	0	0	0	0	0	0
		Confined (365 days year)	0	0	0	0	0	0
	Beef Heifer	Young, not pregnant	322	377	415	503	590	649
		Early gestation	373	438	481	503	590	649
		Late gestation	458	537	591	503	590	649
	Heifers for Slaughter	Feedlot, short-keeps	424	576	628	452	614	670
		Feedlot short-keep long-finish	0	0	0	0	0	0
		Confined	292	397	433	452	614	670
		Pasture	353	479	523	452	614	670
		Feedlot, long-keeps	450	611	667	452	614	670
	Steer	Feedlot, short-keeps	456	578	642	486	617	685
		Feedlot short-keep long-finish	0	0	0	0	0	0
		Confined	314	399	443	486	617	685
		Pasture	380	482	535	486	617	685
		Feedlot, long-keeps	484	614	682	486	617	685
	Calf	Birth to pasture	50	50	50	612	612	612
		Pasture	157	157	157	612	612	612
		Heifer replacement	314	314	314	612	612	612
		Background heifers	316	316	316	612	612	612
		Background steers	316	316	316	612	612	612
ON	Dairy Cow	Lactating, confined	386	386	386	612	612	612
		Lactating, pasture	386	386	386	612	612	612
		Lactating, confined (after pasture)	653	659	655	675	682	678
		Dry, low-quality feed	0	0	0	0	0	0
		Dry, high-quality feed	0	0	0	0	0	0
		Dry, pasture	653	659	655	675	682	678
	Beef Cow	Pregnant, confined	0	0	0	0	0	0
		Lactating, pasture	653	659	655	675	682	678
		Pregnant, confined	540	634	697	540	634	697
		Lactating, pasture	540	634	697	540	634	697
	Bull	Mature, confined	0	0	0	0	0	0
		Mature pasture	0	0	0	0	0	0
		Young confined	790	906	950	790	906	950
		Young pasture	790	906	950	790	906	950
		Young confined	481	552	579	790	906	950
	Dairy heifer	Confined (243 days year)	576	661	693	790	906	950
		Pasture	711	816	855	790	906	950
		Confined (365 days year)	495	500	497	675	682	678
	Beef Heifer	Young, not pregnant	495	500	497	675	682	678
		Early gestation	495	500	497	675	682	678
		Late gestation	349	410	451	540	634	697
	Heifers for Slaughter	Feedlot, short-keeps	420	492	541	540	634	697
		Feedlot short-keep long-finish	520	610	671	540	634	697
		Confined	420	571	623	485	659	719
		Pasture	410	556	607	485	659	719
		Feedlot, long-keeps	358	487	531	485	659	719
	Steer	Feedlot, short-keeps	422	573	626	485	659	719
		Feedlot short-keep long-finish	494	671	732	485	659	719
		Confined	452	574	637	522	662	735
		Pasture	441	559	621	522	662	735
		Feedlot, long-keeps	386	489	543	522	662	735
	Calf	Birth to pasture	454	576	640	522	662	735
		Pasture	532	674	749	522	662	735
		Heifer replacement	75	75	75	658	658	658
		Background heifers	194	194	194	658	658	658
		Background steers	344	344	344	658	658	658

A3.4.1.2. Swine

Production Performance

Trends in carcass weights are used as an indicator of changes in mature weight. Carcass weight data are collected and published by Statistics Canada as part of the quarterly Farm Cash Receipts (FCR) survey (Statistics Canada, n.d.[b]). Average cold-trimmed carcass weights are converted to live weights using the corresponding conversion factor (AAFC, 2018). Since 1990, hog carcass weights have increased steadily from 77 kg to 101 kg (+32%), as a result of a change in production practices and genetics. Relationships between live weight and average daily weight gain, as well as changes in average daily weight gain over time by animal weight class, were developed based on data from the Prairie Swine Research Centre and combined with the time series of mature weights to develop a time series of typical animal mass for market swine. The typical animal mass for market swine varies by weight class (Figure A3.4–3) based on increased rates of growth and, in the case of the upper weight class, an increase in carcass weights since 1990. Animal mass for breeding animals was held constant using the default IPCC value.

A3.4.2. CH₄ Emissions from Enteric Fermentation

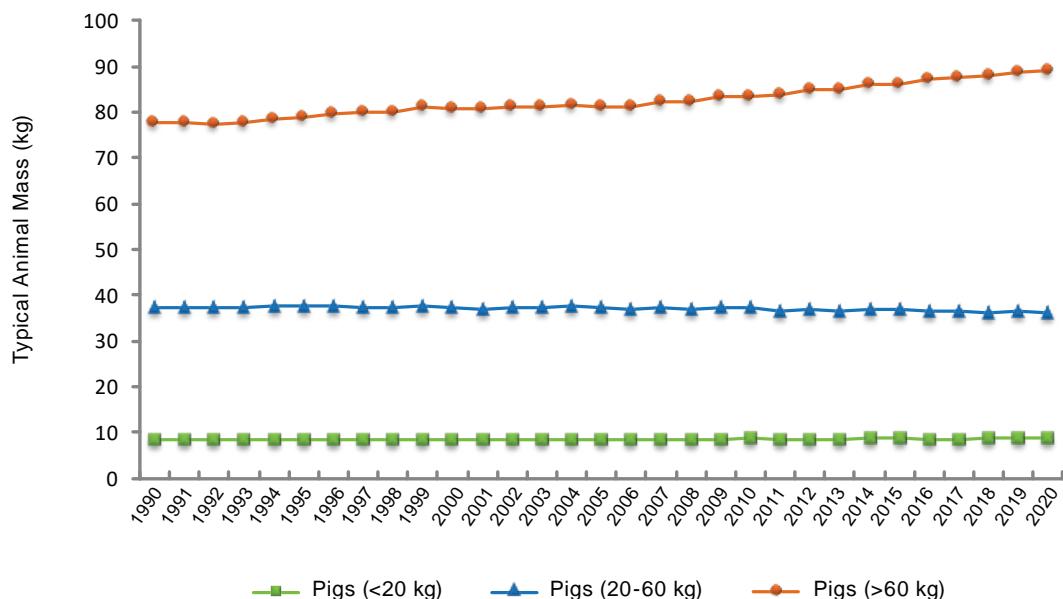
The release of CH₄ from the process of enteric fermentation is calculated using Equation A3.4–1 for all categories of livestock in Canada. CH₄ emissions reported under Enteric Fermentation for cattle are estimated using the country-specific emission factors derived from IPCC (2006) Tier 2 equations (Table A3.4–11). For the other animal categories, the IPCC Tier 1 methodology and default emission factors are applied (see Annex 6).

Equation A3.4–1

$$CH_{4EF} = \sum_T (N_T \times EF_{(EF)T})$$

- CH_{4EF} = CH₄ emissions from the process of enteric fermentation for all animal categories
 N_T = animal population for the T th animal category or subcategory in each province
 $EF_{(EF)T}$ = emission factor for the T th animal category or subcategory (Table A3.4–11 for cattle; for other animal categories, see Annex 6)

Figure A3.4–3 Typical Animal Mass for Swine, by Weight Class



A3.4.2.1. Enteric CH₄ Emission Factors for Cattle

Emission factors were derived at the provincial level using IPCC (2006) Tier 2 equations for different subcategories of cattle (dairy cows, dairy heifers, beef cows, beef heifers, bulls, calves, heifer replacement, heifers > 1 year and steers > 1 year) based on stages of production. Tier 2 enteric fermentation estimates require an approximation of GE consumed calculated according to Equation A3.4–2.

Equation A3.4–2

$$GE = \left[\frac{(NE_m + NE_a + NE_l + NE_p)}{(REM)} \right] + \left[\frac{NE_g}{(REG)} \right] / \left[\frac{DE\%}{100} \right]$$

GE	=	gross energy, MJ day ⁻¹
NE_m	=	net energy required for maintenance, MJ day ⁻¹
NE_a	=	net energy required for activity, MJ day ⁻¹
NE_l	=	net energy required for lactation, MJ day ⁻¹
NE_p	=	net energy required for pregnancy, MJ day ⁻¹
REM	=	ratio of net energy available in a diet for maintenance to digestible energy consumed
NE_g	=	net energy required for growth, MJ day ⁻¹
REG	=	ratio of net energy available in a diet for growth to digestible energy consumed
DE%	=	digestibility of the ration, %

All net energy estimates are applied according to equations in the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). Due to the Canadian climate, Equation 10.2 from the Guidelines (Equation A3.4–3) was implemented for Non-Dairy Cattle.

Equation A3.4–3

$$Cf_i(\text{in cold}) = Cf_i + 0.0048 \times (20 - {}^{\circ}\text{C})$$

Cf_i	=	A coefficient that varies for each animal category relating weight to energy requirements for body maintenance, MJ day ⁻¹ kg ⁻¹
{}^{\circ}\text{C}	=	Mean daily temperature during the winter season

The cold-adjusted Cf_i was derived by using the average temperature for the period October to April for each Canadian province, weighted based on the geographic location of non-dairy types of cattle (distributed at the ecodistrict scale) in the province. It was then corrected based on the percentage of animals kept in barns for different provinces, taken from Sheppard and Bittman (2012) and was applied to all production stages that occur during the winter months. Production stages that occur in both winter and summer, specifically finishing stages for steers and slaughter heifers, were averages of the default and the cold-adjusted Cf_i. As a result of this implementation, considering the different production stages of the animal, average annual Cf_i values varied between 0.43 for non-dairy cows in Manitoba, the coldest province, and 0.37 for non-dairy cows in Ontario and some of the Maritime provinces. Based on a weighting of production stages, the Cf_i would typically be 0.35, not considering the temperature effect. The lower Cf_i in Eastern Canada is due mainly to milder temperatures, but also to the practice of keeping animals in barns over winter, whereas in Western Canada, cattle are mainly kept outdoors. As a result, the impact of cold on the net energy of maintenance is largely observed in Western Canada.

Different stages of production require different consumption patterns to supply the necessary energy for specific animal products and environmental conditions and therefore have different GE values. For example, emissions reported under Dairy Cattle were estimated for two production categories: dry cows and lactating cows. Lactating cattle require high consumption rates (GE) for milk production. Dry cattle may also be confined or on pasture, which also modifies their required energy intake.

The total duration of time an animal spends in a production stage can also be variable, and a weighted average emission factor was therefore calculated. Criteria used in the weighting included duration of time spent in each production stage and relative percentage of the population in each stage of production. Furthermore, some net energy calculations may be modified based on a factor that takes into account the time that the energy is supplied within a production stage.

For each province, an emission factor ($EF_{(EF)}$) is calculated according to Equation A3.4–4. Provincial emission factors were weighted on the basis of the proportion of the provincial animal population relative to the national population to calculate a national emission factor for each subcategory, for each year in the time series (Table A3.4–11). For emission factors reported under Non-Dairy Cattle, the IPCC default methane conversion rate (Y_m) of 6.5% was used to calculate non-feedlot cattle emission factors and 3% was used for animals in feedlots.

The dairy Y_m factor was derived directly from production data and empirical CH_4 prediction equations developed from North American research. Briefly, the farm size by productivity matrix used to derive ration digestibility was also used to provide more detailed feed characteristics such as neutral detergent fibre, fat content and non-fibre carbohydrate content. These feed, herd and production characteristics separated by farm size and productivity class were inserted into 12 predictive methane equations, compiled from three scientific publications (Ellis et al., 2007, 2010; Appuhamy et al., 2016). Gross energy for each production and farm size class was calculated according to Equation A3.4–2 based on the herd specific characteristics. Finally, the Y_m was back-calculated from predicted methane emissions and calculated GE intake.

An average Y_m per productivity and farm size class was calculated based on the results of the 12 predictive equations. This value was then weighted for each province based on the proportional breakdown of the population of animals in each productivity and farm size class in the same way as a provincial digestibility value was derived. The Y_m that was derived varied between 5.9% for the lowest productivity classes and 5.4% for the highest productivity class. Weighted provincial Y_m values varied between 5.5% and 5.7%.

Dry matter intake (DMI) is based on the cattle production approach and calculated at the provincial level based on regional trends and seasonal stages of production. Weighted national DMI (Table A3.4–10) for dairy cows has increased by 24% since 1990 in response to increased milk production per cow (Table A3.4–4), while DMI for dairy heifers decreased by 3% over this period due to increased feed digestibility resulting from changes in ration composition. For beef cattle, DMI is driven by trends in carcass weights (Figure A3.4–2).

Table A3.4–10 Dry Matter Intake (DMI) by Cattle Subcategory, for Select Years from 1990 to 2020, estimated from Gross Energy (GE) Intake

Year	DMI (kg DM head ⁻¹ day ⁻¹)							
	Dairy Cows	Dairy Heifers	Bulls	Beef Cows	Beef Heifers	Heifers for Slaughter ^a	Steers ^a	Calves
1990	17	10	14	13	10	10	9	6
1995	17	10	15	14	11	11	10	7
2000	18	10	15	15	11	11	10	7
2005	18	10	15	15	11	11	10	7
2010	19	10	16	15	11	11	10	7
2011	19	10	16	15	11	11	10	7
2012	19	10	17	15	11	12	11	7
2013	19	10	15	15	11	12	10	7
2014	19	10	15	15	11	11	10	7
2015	20	10	16	15	12	12	11	7
2016	20	10	16	15	12	12	11	7
2017	20	10	17	15	12	12	11	7
2018	20	10	16	15	12	12	11	7
2019	21	10	16	15	12	12	11	7
2020	21	10	16	15	12	12	11	7

Note:

a. Reported as kg head⁻¹ day⁻¹; however, emissions are calculated based on time to slaughter.

Table A3.4-11 **CH₄ Emission Factors for Enteric Fermentation for Cattle in Select Years from 1990 to 2020**

Year	EF _{(EF)T} (kg CH ₄ head ⁻¹ year ⁻¹) ^a							
	Dairy Cows	Dairy Heifers	Bulls	Beef Cows	Beef Heifers	Heifers for Slaughter ^b	Steers ^b	Calves
1990	115.4	79.4	108.0	105.9	82.5	44.7	41.4	43.8
1995	119.1	78.6	117.2	112.1	85.9	48.8	43.6	43.8
2000	125.4	78.0	121.0	117.5	89.4	53.0	47.8	43.8
2005	125.0	77.2	119.9	114.4	87.0	52.8	46.0	43.6
2010	128.6	76.8	128.5	115.2	87.8	52.8	47.0	43.7
2011	129.2	76.8	127.6	115.0	87.5	52.7	47.4	43.7
2012	129.6	76.8	129.8	115.6	87.6	53.8	48.0	43.7
2013	134.0	76.8	117.1	115.3	87.5	53.7	48.0	43.8
2014	134.1	76.7	121.1	116.3	88.1	53.2	48.1	43.8
2015	135.2	76.7	127.5	120.0	90.7	53.8	48.8	43.8
2016	137.5	76.7	128.0	121.3	91.6	53.9	48.8	43.8
2017	138.1	76.7	130.1	120.8	91.3	53.6	48.4	43.8
2018	139.6	76.7	125.3	120.5	91.2	53.7	48.5	43.8
2019	142.2	76.6	124.0	120.3	91.0	53.9	49.0	43.7
2020	142.9	76.6	123.9	120.3	91.0	54.0	49.0	43.8

Notes:

- a. Enteric emission factors are derived from Boadi et al. (2004b), modified to take into account trends in milk production in dairy cows and carcass weights for several beef cattle categories.
b. Reported as kg head⁻¹ yr⁻¹; however, emissions are calculated based on time to slaughter.

Equation A3.4-4

$$EF_{(EF)T} = \sum_T \left[\frac{GE_P \times Y_{mP} \times 365}{55.65} \times TP_P \right]$$

$EF_{(EF)T}$	=	annual emission factor for defined animal population T , kg head ⁻¹ yr ⁻¹
GE_P	=	gross energy for a given cattle stage of production P , MJ day ⁻¹
Y_{mP}	=	methane conversion rate at which the fraction of GE is converted to methane by an animal within defined population T , m ³ kg ⁻¹
55.65	=	energy content of methane, MJ kg ⁻¹ CH ₄
TP_P	=	time within a stage of production P , days yr ⁻¹

A3.4.2.2. Verification of Parameter Selection Against Canadian Research

In 2011, an internal Tier 2 quality assurance/quality control (QA/QC) was carried out on the Enteric Fermentation source category (MacDonald and Liang, 2011). In this analysis, a review and compilation of Canadian literature related to methane production from the process of enteric fermentation were carried out. The results were then evaluated in light of the implementation of the 2006 IPCC Guidelines.

The 2011 analysis research measuring enteric fermentation processes in Canada indicates that the average measured Y_m is 6.6% (± 2.4) of GE for non-dairy cattle animals outside of feedlots, 3.2% (± 1.9) of GE for non-dairy types of cattle on feedlots and 5.7% (± 0.9) for dairy livestock (McCaughay et al., 1997, 1999; Boadi and Wittenberg, 2002; Boadi et al., 2002, 2004b; McGinn et al., 2004, 2008, 2009; Beauchemin and McGinn, 2005, 2006; Chaves et al., 2006; Kebreab et al., 2006; Ominski et al., 2006; Odongo et al., 2007; Eugène et al., 2008; Van Haarlem et al., 2008; Beauchemin et al., 2009; Ellis et al., 2010; Jayasundara et al., 2016). For the Non-Dairy Cattle category, these values agree broadly with the values published in the 2006 IPCC Guidelines. Recent work by Escobar-Bahamondes et al. (2016) suggests that further differentiation of Y_m factors by production subcategory is possible, which could aid in improving the accuracy of emission estimates. From the same compilation of research, the emission factor for the Non-Dairy Cattle category is observed to be 57 (± 22) kg CH₄ head⁻¹ yr⁻¹ outside of feedlots and 56 (± 24) kg CH₄ head⁻¹ yr⁻¹ in feedlots, and the average measured emission factor for the Dairy Cattle category is 130 (± 34) kg CH₄ head⁻¹ yr⁻¹.

Caution must be used in interpreting these values because this data set did not include animals in cold conditions and because the majority of studies focus on yearling heifers and steers. Also, the average value does not take into account the relative importance of different cattle subcategories to the average emission factor. Nonetheless, the emission factor values do agree, in general, with the emission factors used by Canada for the Non-Dairy Cattle category (i.e., 60 to 70 kg CH₄ head⁻¹ yr⁻¹) and Dairy Cattle category (i.e., 115 to 137 kg CH₄ head⁻¹ yr⁻¹). A recent publication by Jayasundara et al. (2016) compiled literature data from 11 studies and found that Y_m factors for Canadian dairy livestock were on average 5.7 ($\pm 0.9\%$). In the current Canadian cattle approach, Y_m for dairy cows is varied over time and by province, averaging 5.5%–5.7% of GE, while a fixed Y_m of 6.5% is used for dry dairy cows, dairy heifers.

As it currently stands, no evident bias could be identified from the review of Canadian literature results. It appears that a bias that is introduced through the use of the Y_m values from the 2006 IPCC Guidelines is compensated for by the estimate of GE for specific animal subcategories.

Researchers from Canada have participated in some extensive reviews and validations of the IPCC Tier 2 enteric fermentation method comparing measured and observed emissions using Canadian data. In general, their analysis indicates that the IPCC Tier 2 method tends to underestimate high-emitting animals and overestimate low-emitting animals (Ellis et al., 2007, 2009, 2010).

Improvements to the dairy methodology in the 2018 national inventory report, in particular with the Y_m derived directly from empirical relationships from North American studies, assure that emission rates are consistent with recent measurements of CH₄ emissions, greatly improving the accuracy of emission estimates. Similar approaches would significantly improve estimates for the Non-Dairy Cattle category, but data are still being compiled to carry out these studies. In general, it is difficult to improve Canadian estimates through updates of single parameters. Improving on the current approach requires a comprehensive approach effectively linking regional animal production characteristics to animal productivity, as has been done for the Dairy Cattle category.

A3.4.2.3. Enteric CH₄ Emission Factors for Non-Cattle

For non-cattle animal categories, IPCC Tier 1 emission factors are used to calculate emissions (see Annex 6). When default emission factors are not available for the minor livestock categories, logical proxies are used to estimate emissions; swine emission factors are used for wild boars, and sheep emission factors are used for llamas and alpacas. These proxies are based on species similarities as well as similarities in production practices. Emissions from llamas and alpacas are combined because population totals are not available separately and there is no indication of the ratio of these animals in Canadian statistics..

A3.4.2.4. Uncertainty

A comprehensive uncertainty analysis was carried out on all methodologies used in the calculation of methane from livestock for 2010. Uncertainty ranges (percentages) of means were rerun for the 2014 NIR submission and have not been rerun since that submission. In the analysis, a stochastic reproduction of the livestock CH₄ emission quantification approach was built in Mathematica® and a Monte Carlo simulation (MCS) was run according to the methodology proposed in the IPCC Good Practice Guidance (IPCC, 2000). This analysis built on a recent study (Karimi-Zindashty et al., 2012). However, the Environment Canada stochastic model (ECSM) built in Mathematica® (1) applied the exact parameters and equations used in the Canadian inventory methodology based on the Good Practice Guidance (IPCC, 2000); (2) included uncertainty associated with populations and duration of production stages, which impact subcategory emission factors (Table A3.4–12); and (3) used the provincial distribution of manure management systems with improved estimates of probability distributions (Table A3.4–12). The ECSM was run for the years 1990, 2005, 2010 and 2012. A trend analysis was carried out to establish the uncertainty in the estimate of the differences in emissions from 1990 to 2012. The relative uncertainties from the previous analysis were applied to the current year's values. Uncertainty analysis on the revised dairy methodology, however, has not yet been carried out and reported uncertainty estimates are based on the Boadi et al. (2004a) methodology.

Currently, the data required to create probability distributions of the coefficients used in the agricultural IPCC Tier 2 method simply do not exist. Some of the default coefficients in Tier 2 equations are provided with an uncertainty range, often estimated by expert opinion; for other coefficients, ranges are taken from a few studies, often using methodologies that are not easily comparable. In general, the analysis of Rypdal and Winiwarter (2001) applies to the agricultural emission estimation approach as a whole, and it can be understood that large probability distributions are associated with default Tier 2 coefficients due to a lack of appropriate measurements and subsequent generalizations, uncertainties in measurements and an inadequate understanding of emission processes. This initial uncertainty analysis has applied a precautionary principle, and for coefficients with very little information, uncertainty bounds were conservative.

Uncertainties in populations of major animal categories, i.e., cattle, swine and sheep, were supplied directly by Statistics Canada based on biannual and quarterly survey statistics. For small provinces with few animals in certain categories, sample variance is large, as indicated by uncertain values of > ±50%. However, because the data were collected based on

a sampling design proportional to population distributions, the overall uncertainty for major animal categories at the national level was low. National populations for non-dairy cattle types have the lowest uncertainty ($\pm 1.8\%$ of the mean), with slightly higher uncertainty for swine ($\pm 2.6\%$ of the mean), dairy cattle ($\pm 5.4\%$ of the mean) and sheep ($\pm 6.0\%$ of the mean).

All other animal population estimates are renewed only through the COA. To account for the increase in uncertainty due to the time that has elapsed since the census, a procedure was developed that estimated the increase in uncertainty as a function of time from the census. A linear regression was run through census year population estimates from 1991, 1996, 2001, 2006 and 2011. The uncertainties for populations in 2012 were estimated as the agricultural census uncertainty at the provincial level plus the 95% confidence interval for the linear regression multiplied by the number of years since the last census (one year). Due to the recent COA, the other animals tended to have lower population uncertainties in the 2012 analysis than the 2010–2011 uncertainties, similar to those animals for which population estimates are taken from biannual and quarterly surveys, though this had little impact on total uncertainty. The national population uncertainties for other animal categories ranged from $\pm 2\%$ of the mean for poultry to $\pm 4\%$ of the mean for bison; however, these animal categories contribute little to total emissions.

The parameters used in the calculation of Tier 2 emission factors for cattle can be divided into two categories: (1) those associated with cattle production and performance (see section A3.4.2 for detailed descriptions of parameters); and (2) those that are specific to the IPCC Tier 2 equations (see section A3.4.2 for details). For the most part, the uncertainty assigned to parameters associated with cattle production and performance is relatively low, as these estimates are collected on a provincial basis, from provincial experts, and are values that are generally known within the industry. The largest source of uncertainty in production practices is the duration and fraction of animal populations in specific production stages. This source of uncertainty is associated with the number of animals that are backgrounded and the duration of that backgrounding period. These are parameters that are highly dependent on prices and import/export markets, and therefore confidence in the values that are currently being used is low. A high level of uncertainty (30%) was applied to the number of animals backgrounded, and a non-symmetrical triangular distribution was applied to the duration of backgrounding as a precautionary approach to account for high levels of potential variability in these production practices. The uncertainty in production population fraction and the duration of production stages was not accounted for directly in Karimi-Zindashty et al. (2012).

The uncertainties for parameters used in IPCC Tier 2 equations were taken, for the most part, directly from Karimi-Zindashty et al. (2012), who used the probability distributions either from Monni et al. (2007) or from the 2006 IPCC Guidelines. Two differences are notable: (1) digestible energy probability distributions became available from data supplied by Lactanet after the Karimi-Zindashty et al. (2012) study was completed, allowing the calculation of typical distributions of different types of feed; and (2) Karimi-Zindashty et al. (2012) used the 2006 IPCC methodology and therefore did not include the effects of weight loss on GE. A uniform distribution was therefore used in the ECSM analysis to account for the impact of incorporating an estimate of net energy mobilized through weight loss during lactation (NE_{mob}) that varied according to duration of weight loss between 0% and 20% of the lactation period. As this parameter has been removed from the 2006 IPCC Guidelines, this approach was an effective way to evaluate the overall impact of this parameter.

A trend analysis was carried out using the ECSM in which the uncertainty in the magnitude of the change in emissions over time was calculated. For the long-term trend, emissions for 1990 and 2012 were calculated simultaneously, allowing only time-dependent parameters to vary independently in the estimates. These parameters represent the elements of the calculation approach that change over time, and therefore an estimate is available for a value in 1990 and in 2012 (noted by a superscript 7 in Table A3.4–12). The parameters in 1990 and 2012 are considered entirely independent and, as a consequence, for each calculation in the MSC, a value was selected from the probability distribution for 1990 and 2012 independently. In contrast, other parameters used a value selected once from their probability distribution for the calculation of emissions in both 1990 and 2012. The parameters that were allowed to vary independently for the enteric fermentation process analysis were animal populations, milk production and fat content for dairy cows, and body weights for cattle. The relative uncertainty values for the trend analysis were applied to the 2013 results.

The summary results of the uncertainty analysis for emissions from the process of enteric fermentation are reported in Chapter 5, section 6.2.3. Briefly, the fixed range used in calculating uncertainty ranges for emissions from enteric fermentation is 39% (-17% to +22% of the mean) (see Chapter 5). Most uncertainty in the estimate is associated with the Tier 2 emission factors for cattle; they lie within an uncertainty range of -19% to +22% of the mean emission factor for the Non-Dairy Cattle category and -16% and +21% of the mean emission factor for the Dairy Cattle category. In the case of other animals that use Tier 1 IPCC (2006) default emission factors, uncertainty ranges of $\pm 50\%$ were assigned, with the exception of swine, which was $\pm 37\%$ based on Monni et al. (2007). Relative to cattle, the Tier 1 emission factors for other animals have little impact on the total uncertainty because of the small contribution of other animal categories to total enteric fermentation emissions. Mean emissions for both the Dairy Cattle and Non-Dairy Cattle categories estimated using the stochastic model are slightly higher than calculated in the inventory database (roughly 2%). This difference is likely due to the introduction of the non-symmetrical triangular distribution that increased the length of backgrounding for slaughter heifers and steers and to the uniform distribution of the factor that defines energy released from weight loss during lactation in dairy cows.

The overall uncertainty for each estimate of each individual year changes little over time. The uncertainty range for emissions in 1990 and 2012 is 39% to 40%. Based on the trend analysis, over the long term, CH_4 emissions increased between the 1990 base year and 2012 by 9% to 19%, with a most likely value (MLV) of 15% (trend uncertainty 10%). Most of the increase in emissions is associated with the Enteric Fermentation category, which increased by 11% to 22%, with an MLV of 16%. To estimate the trend uncertainty reported in Chapter 5, the relative trend uncertainties from the previous analysis were applied to the current year's mean change in emissions. In general, this uncertainty analysis was consistent with other agricultural estimates of uncertainty. The paper by Monni et al. (2007) is, to our knowledge, currently the only one detailing agricultural CH_4 emission uncertainty with the use of IPCC Tier 2 methodology. The use of comparable probability distributions for IPCC Tier 2 default parameters provides comparability between the two different national emission estimation methodologies. Monni et al. (2007) estimated the national-scale uncertainty for Enteric Fermentation emissions from Finnish agriculture for different cattle subcategories as ranging from -22% to +29% of the mean to -29% to +39% of the mean. Rypdal and Winiwarter (2001) reported uncertainties for some European countries ranging from $\pm 20\%$ of the mean in the United Kingdom to $\pm 50\%$ of the mean in Austria, but they used mainly Tier 1 estimation methodologies. We did not find comparable publications for trend uncertainty analysis in the field of agriculture.

The results of this uncertainty analysis were, of course, very similar to those produced by Karimi-Zindashty et al. (2012), who also observed an overall uncertainty range for enteric fermentation emissions of 39%, indicating that the uncertainty associated with the production stage duration and population fractions had little impact on the overall uncertainty. The incorporation of the uncertainty associated with weight loss during lactation did not increase overall uncertainty, but tended to skew the uncertainty distribution for Dairy Cattle category estimates towards higher emission estimates. The sensitivity analysis carried out by Karimi-Zindashty et al. (2012) indicated that the major drivers of uncertainty in emission estimates were associated with the default IPCC Tier 2 parameters, in particular the methane conversion rate (Y_m) and the factor associated with the net energy of maintenance (C_f), applied at the national scale. Uncertainty in the Tier 2 methodology may be reduced through the development of country-specific parameters at the regional scale for different animal categories. It is suspected that the recent revisions to the dairy methodology will have reduced the overall uncertainty of enteric emission estimates; however, further analysis is required to quantify the impact of improvements on the uncertainty estimates.

A3.4.3. CH_4 Emissions from Manure Management

The IPCC Tier 2 methodology is used to estimate CH_4 emission factors from manure management systems (IPCC, 2006), also referred to as animal waste management systems (AWMS). Equation A3.4–5 is used to calculate CH_4 emissions from the management of manure for all categories of livestock in Canada with the exception of deer and elk, rabbits, mules and asses, and fur-bearing animals, which were calculated using IPCC Tier 1 emission factors. Wild boar emission factors were calculated based on average swine Tier 2 parameters, but assuming only solid manure. Sources of animal population data are the same as those used in the reporting of Enteric Fermentation estimates and are listed in Table A3.4–1.

When default emission factors or country-specific information sources are not available for the minor livestock categories, logical proxies are used to estimate emissions. These proxies are based on species similarities as well as similarities in production practices. When proxies are used at a provincial level, weighted national values may not match between the native and proxy livestock categories due to differences in provincial populations used for weighting.

The following proxies and expert judgement are used for minor animal categories:

- Manure management system parameters from the Non-Dairy Cattle category are used to represent bison, including the maximum CH_4 producing potential (B_0) and provincial AWMS distributions.
- Provincial AWMS distributions for horses are used to represent mules and asses.
- Provincial AWMS distributions for the Non-Dairy Cattle category are used for the reporting of Deer and Elk, except that liquid systems are distributed to PRP based on expert judgement that deer and elk livestock manure is unlikely to be handled by liquid manure systems.
- Volatile solids (VS) for the Swine category are used to represent wild boars at a provincial level. The disaggregation of swine animal subcategories and scaling of VS with animal mass (section A3.4.3.6) are not used for this proxy relationship. Lastly, all manure from wild boar livestock is allocated to solid AWMS based on expert judgement.
- Sheep manure management system parameters are used to represent llamas and alpacas, including volatile solids and provincial AWMS distributions.

Total emissions from the minor animal categories Mules and Asses, Deer and Elk, Llamas and Alpacas, Mink, Foxes, Rabbits and Wild Boars represented less than 100 kt CO_2 eq in 2019 (<0.2% of total agricultural emissions), including direct and indirect emissions and emissions from application to agricultural soils. Changes to these proxies could not have a significant impact on emission estimates from the agricultural sector, and based on the insignificant impact of these animal categories on agricultural emissions, improvements to these animal categories are of the lowest priority in the agricultural inventory.

CH_{4MM}	=	emissions for all animal categories
N_T	=	animal population for the T th animal category or subcategory in each province
$EF_{(MM)T}$	=	emission factor for the T th animal category or subcategory calculated according to Equation A3.4–6

To develop Tier 2 CH_4 emission factors representing manure management systems, country-specific inputs were required that take into account climate, livestock rations and the type of manure storage system included in Equation A3.4–6. The following equation represents an IPCC Tier 2 estimate of CH_4 emission factors from manure management systems:

Equation A3.4–6

$EF_{(MM)T} = VS_T \times 365 \times B_{0T} \times 0.67 \text{ kg m}^{-3} \times \sum_{ij} MCF_{ij} \times AWMS_{Tij}$		
$EF_{(MM)T}$	=	annual emission factor for defined animal population T , $\text{kg CH}_4 \text{ head}^{-1} \text{ yr}^{-1}$
VS_T	=	daily volatile solids excreted for an animal within the defined population T , kg day^{-1}
B_{0T}	=	maximum CH_4 producing potential for manure produced by an animal within defined population T , $\text{m}^3 \text{ kg}^{-1} \text{ VS}$
MCF_{ij}	=	CH_4 conversion factor for each manure management system i in climate region j
$AWMS_{Tij}$	=	system distribution factor, defined as the fraction of animal category T 's manure that is handled using manure system i in climate region j , often referred to in IPCC documents as management system (MS)
0.67	=	conversion factor of $\text{m}^3 \text{ CH}_4$ to kilograms CH_4

The following sections outline the sources of input values for VS, DE%, ASH, B_0 , MCF and AWMS.

A3.4.3.1. Volatile Solids (VS)

Cattle, VS

Volatile solids are the organic fraction of total solids in manure. The VS of manure was estimated using the digestibility (DE%) of dietary intake, manure ash content and GE consumed by a given animal subcategory, and the urinary energy (UE) fraction of the GE intake, according to the 2006 IPCC Guidelines.

For cattle subcategories, the GE depends on the cattle production system based approach defined for estimating emissions from the enteric fermentation process (Boadi et al., 2004a), as shown in Equation A3.4–3. Estimates of VS were derived for each cattle subcategory at the provincial level based on regional and seasonal stages of production (Equation A3.4–7). Increases in milk production in dairy cows and carcass weight in beef cattle have increased VS with increased dry matter intake and, as a result, CH_4 emission factors over the time series; however, increases of DE% in dairy feed over time have moderated this effect for dairy cows.

Equation A3.4–7

$VS = \left[GE \times \left(1 - \frac{DE\%}{100} \right) + (UE \times GE) \right] \times \left(\frac{1 - ASH}{18.45 \text{ MJ}} \right)$		
VS	=	volatile solids excretion, $\text{kg head}^{-1} \text{ yr}^{-1}$
GE	=	gross energy consumed by a given animal, $\text{MJ head}^{-1} \text{ yr}^{-1}$
$DE\%$	=	digestibility of the ration, %
UE	=	urinary energy (unitless)
ASH	=	ash fraction of the manure, %

Table A3.4–12 Uncertainties in Inputs, Sources of Uncertainty and the Spatial Scale and Animal Category to Which Uncertainty is Assigned, for Parameters Used for Estimating Methane Emissions from Enteric Fermentation

Parameter Category	Parameter	Coefficient/Parameter Source	Distribution Type	Uncertainty Range ^a	Uncertainty Distribution Source and Notes	Spatial Allocation/Animal Category Allocation
Population Data^b						
Cattle Biannual Surveys						
	Dairy	Statistics Canada (Table 003-0032)	normal	±6% – ±42%	Karimi-Zindashty et al. (2012) from Statistics Canada, personal communication ^c	Provincial/subcategory
	Non-dairy			±5% – ±73%		
Other Survey-based Populations						
	Swine	Statistics Canada (Tables 003-0004 and 003-0031)		±8% – ±89%		
	Sheep			±14% – ±80%		
Census of Agriculture						
	Goats	Census of Agriculture (Statistics Canada, 2012a)		±9% – ±21%	Statistics Canada, <i>Census of Agriculture</i> plus uncertainty associated with linear extrapolation, function of time from census	
	Poultry			±5% – ±12%		
	Bison			±18% – ±85%		
	Llamas and Alpacas			±16% – ±42%		
	Horses			±5% – ±16%		
Cattle Production Parameters and Performance						
	Milk production ^b	Valacta/Canwest DHI	normal	±8%	Karimi-Zindashty et al. (2012) – from expert opinion	Provincial/subcategory
	Fat content ^b	Valacta/Canwest DHI				
	Dairy herd efficiency ^b	Valacta/Canwest DHI	normal	±5%	Karimi-Zindashty et al. (2012) – from expert opinion	
	Pregnancy coefficient	Boadi et al. (2004b)				
	Average daily gain (ADG)	Boadi et al. (2004b)				
	Pregnancy period	Boadi et al. (2004b)				
	Production stage duration	Boadi et al. (2004b)	normal except slaughter animals, triangular, non-symmetric	±5%, Slaughter animals: MLV ^f from Boadi et al. (2004b) LB: 12% of MLV; UB: 25% of MLV	Expert opinion, Boadi et al. (2004b) – for feeder heifers and steers, a triangular distribution was assumed based on interpretation of potential market effects (Canfax Research Services, 2009)	Provincial/production stage subcategory, internal correlation ^g
	Production stage population fraction	Boadi et al. (2004b)		normal	±5% – ±30%	
Cattle Weight Estimates^b						
	Live weight, 2001	Boadi et al. (2004b)	normal	±5%	Karimi-Zindashty et al. (2012) – from expert opinion	Provincial/production stage subcategory
	Mature weight, 2001	Boadi et al. (2004b)				
	Carcass weight	CBGA ^d and published AAFC ^e (1990–2010)				National/subcategory
Emissions Factors for Cattle (IPCC Tier 2 Equations)						
	Methane conversion rate (Y_m)		normal	Feedlot animals – ±30% Other animals – ±15%	Karimi-Zindashty et al. (2012) – IPCC (2006)	National/feedlot vs. non feedlot
Gross Energy for Cattle Calculation IPCC Tier 2 Equation A3-18						
	Digestible energy (DE)	Boadi et al. (2004b)	normal	Pasture ±9% Confined ±9% Background ±7.5% Prepared feed ±5.5%	Derived from raw data supplied by Valacta Dairy Services	Provincial/production stage subcategory
Net Energy for Cattle Tier 2 Equations 4.1 to 4.10, IPCC Good Practice Guidance (2000)						
	Animal activity coefficient (C_a)	IPCC (2000)	normal	±30%	Karimi-Zandashy et al. (2012) – Monni et al. (2007)	National/cattle
	Gender coefficient (C)		normal	±30%		
	Maintenance coefficient C_f			±30%		
	Lactation coefficient			±30%		
	Weight loss rate		normal	5%	Karimi-Zindashty et al. (2012) – from expert opinion	Provincial/subcategory
	Weight loss duration		uniform	LB: 0 UB: 20% of lactation period.		
Non-cattle Emission Factors						
	Swine	IPCC (2000)	normal	±37%	Karimi-Zandashy et al. (2012) – Monni et al. (2007)	National/category
	Other animals			±50%		

Notes:

- a. Where differences in uncertainty exist for different provinces or animal categories, maximum and minimum uncertainties are given.
- b. Values that were allowed to vary independently during trend analysis.
- c. Personal communication. Plourde R, Statistics Canada, Livestock and Food Section, Ottawa, ON. April 4, 2010.
- d. Canadian Beef Grading Agency.
- e. Agriculture and Agri-Food Canada.
- f. MLV = most likely value; LB = lower bound; UB = upper bound.
- g. Internal correlation indicates values that vary in terms of a fraction of the whole, i.e., a fraction of a total equalling 100%.

Swine, VS

Volatile solids reported for the Swine category (Table A3.4–14) were estimated by first calculating provincial VS excretion based on values in Marinier et al. (2004), using the IPCC 2006 Tier 2 approach and taking into account the variability in the values of DMI, DE% and ASH derived from expert surveys. Typical animal mass was used to convert the temporally fixed VS into units of VS per 1000 kg body weight ($\text{kg VS 1000 kg animal mass}^{-1} \text{ day}^{-1}$), which was then applied to the full animal mass time series.

All Other Animals, VS

Volatile solids for animal categories other than Dairy Cattle, Non-Dairy Cattle and Swine were calculated based on values in Marinier et al. (2004), using the IPCC 2006 Tier 2 approach and taking into account the variability in the values of DMI, DE% and ASH derived from expert surveys. The values for DMI, DE% and ASH taken from that survey were used to calculate VS for non-cattle livestock categories for each individual province (Equation A3.4–8). Confidence intervals were developed using a MSC performed with Crystal Ball® (Decisioneering, 2000), resulting in a probability distribution based on the variance in expert opinion and scientific literature (Table A3.4–13).

Table A3.4–13 Mean Volatile Solids in Manure of Non-Cattle Animal Categories in 2020 and Associated 95% Confidence Interval, Expressed as a Percentage of the Mean

Animal Category	Mean Volatile Solids ($\text{kg head}^{-1} \text{ day}^{-1}$)	95% Confidence Interval (%)
Sheep and Lambs ^a	0.60	31
Mature Horses	3.6	16
Goats	0.72	41
Bison	3.1	16
Wild Boars ^b	0.24	50
Poultry	0.02	20

Notes:

a. Llamas and alpacas are given the same values as sheep at the provincial level, and weighted based on the population of llamas and alpacas in each province.

b. The value for wild boars is calculated on the basis of the value for swine.

Table A3.4–14 Mean Volatile Solids in Swine Manure in 2020

Animal Category	VS ($\text{kg 1000 kg body mass}^{-1} \text{ day}^{-1}$)	Typical Animal Mass (kg)	VS (kg day^{-1})
Sows	1.6	198	0.31
Boars	1.6	198	0.31
Pigs (<20 kg)	10.9	8.8	0.09
Pigs (20–60 kg)	5.2	36	0.19
Pigs (>60 kg)	4.6	89	0.40

$$VS = \left[DMI \times 18.45 \times \left(1 - \frac{DE\%}{100} \right) + (UE \times DMI \times 18.45) \right] \times \left(\frac{1 - ASH}{18.45 \text{ MJ}} \right)$$

VS	=	volatile solids excretion, kg head ⁻¹ yr ⁻¹
DMI	=	dry matter intake, kg head ⁻¹ yr ⁻¹
DE%	=	digestibility of the ration, %
UE	=	urinary energy (unitless)
ASH	=	ash content of the manure, %

The following sections outline the data for estimating VS developed by Marinier et al. (2004).

Digestibility (DE%) and Dry Matter Intake (DMI)

The sources of information used for DE% for both the Dairy Cattle and Non-Dairy Cattle categories are detailed in section A3.4.1.1.

Broad regional differences in ration composition were identified for sheep, horses and swine livestock. Regional differences were not considered for goats or poultry livestock, since these data were not available.

Generally, rations for grazing livestock consist of roughage and grains. Diet digestibility will vary, with grains having a higher digestibility than roughage. The distribution of grain-based and roughage-based diets was estimated for sheep and horses in each province. A weighted estimate of DE% was calculated using the known approximate DE% for grains and roughage for each animal type and the distribution of grain and roughage usage by province (Table A3.4-15). This method does not, however, account for additives that may increase or decrease digestibility. The DMI for non-cattle animal categories was determined through consultation with experts and published values (Table A3.4-16).

Manure Ash Content (ASH)

The ash content in the manure is the inorganic portion of the manure. Table A3.4-17 contains the values used in this inventory for ash content in volatile solid calculations and their sources.

Table A3.4-15 Approximate Ration Digestibility (DE%) for Selected Livestock Subcategories and Data Sources

Animal Category	DE (%)	Data Sources
Goats	65	W. Whitmore, Manitoba Agriculture and Food
Laying Hens	80	S. Leeson, University of Guelph; D. Korver, University of Alberta
Chickens	80	S. Leeson, University of Guelph; D. Korver, University of Alberta
Turkeys	78	S. Leeson, University of Guelph
Swine	87	C.F. deLange, University of Guelph
Feeding on Grain Diet		
Sheep	74	Weston (2002)
Horses	70	L. Warren, Colorado State University
Feeding on Roughage Diet		
Sheep	65	W. Whitmore, Manitoba Agriculture and Food
Horses	60	L. Warren, Colorado State University
Note:		
Data source = Expert consultations (Marinier et al., 2004).		

Table A3.4–16 Dry Matter Intake for Selected Livestock

Animal Category	(kg head ⁻¹ day ⁻¹)	Data Sources
Sheep and Lambs		
Ewes	1.2–2.8	NRC (1985)
Rams	2.1–3.0	W. Whitmore, Manitoba Agriculture and Food
Replacement Lambs	1.2–1.5	NRC (1985)
Market Lambs	1.3–1.6	NRC (1985)
Horses		
Mature Idle Horses	7.4–11	NRC (1989); L. Warren, Colorado State University
Mature Working Horses	7.4–13.7	NRC (1989); L. Warren, Colorado State University
Weanlings	3.6–6.3	NRC (1989)
Swine		
Starters (5–20 kg)	0.55–0.72	C. Wagner-Riddle, University of Guelph
Growers (20–60 kg)	1.4–2.1	J. Patience, Prairie Swine Centre
Finishers (60–110 kg)	2.1–3.3a	M. Nyachoti, University of Manitoba; C. Pomar, Agriculture and Agri-Food Canada
Sows	2.28	C. Wagner-Riddle, University of Guelph
Boars	2.0–2.5	M. Nyachoti, University of Manitoba; NRC (1998)
Goats		
Does	1.2–2.8	NRC (1981)
Bucks	1.4–2.3	CRAAQ (1999)
Kids	1.4	CRAAQ (1999)
Poultry		
Laying Hens	0.072–0.11	S. Leeson, University of Guelph; D. Korver, University of Alberta
Broilers	0.085–0.088	S. Leeson, University of Guelph; D. Korver, University of Alberta
Turkeys	0.023–0.53	Hybrid (2001)
Notes:		
Data source: Expert consultations (Marinier et al., 2004).		
a. Calculated as 3.5% of body weight.		

Table A3.4–17 Manure Ash Content for Selected Livestock and Data Sources

Animal Category	ASH (%)	Data Sources
Cattle	8	IPCC (2000)
Sheep	8	IPCC (2000)
Goats	8	IPCC (2000)
Horses	4	IPCC (2000)
Laying Hens	10	Marinier et al. (2004)
Chickens	7	Marinier et al. (2004)
Turkeys	5	Marinier et al. (2004)
Swine	5	Marinier et al. (2004)
Wild Boars	5	Swine used as a proxy

A3.4.3.2. Maximum CH₄ Producing Potential (B₀)

The B₀ is defined as the maximum volume of CH₄ that can be produced from 1 kg of VS loaded into a manure management system and is expressed as m³ kg⁻¹ VS loaded. The values published in the 2006 IPCC Guidelines were used for all animals. For bison, the values of the Non-Dairy Cattle category were used.

A3.4.3.3. Animal Waste Management System (AWMS) Distribution Factor

The AWMS factor is the proportional distribution of AWMS of a livestock category within a given area. There is little reliable published information on the distribution of manure management systems in Canada.

Anaerobic treatment lagoons and daily spread are not typically used for manure storage in Canada. Though some examples may exist, they cannot be quantified and, for this reason, are currently considered non-significant and are not estimated. The existence of these types of systems was not identified in the expert consultation carried out by Marinier et al. (2004) or across Farm Environmental Management Surveys (FEMS), which are the sources of AWMS allocation data for Canada. Therefore, the amount of manure treated by these systems is assumed to be negligible. Earthen storage systems exist in Canada, but in these storage systems, solids are removed regularly when the storage systems are emptied on an annual basis and there is no long-term accumulation and anaerobic treatment of solids in the lagoon, as is the case with “anaerobic treatment lagoons” as defined by the IPCC guidelines.

Dairy

For the Dairy Cattle category, a relationship between farm size and time spent on pasture, in exercise yards and in barns was developed from Sheppard et al. (2011) for each province. The proportion of manure excreted in each of these locations is assumed to be equal to the time spent in each area. Time spent on pasture was found to decrease with increasing farm size, and the fraction of manure deposited on pasture decreased on average from 19% in 1990 to 16% in 2016 due to a shift towards larger farm operations.

For manure deposited in barns, a manure storage time series was developed from a combination of data from the Farm Inputs Management Survey (1995), the Farm Environmental Management Surveys (2001, 2006, 2011) and the Livestock Farm Practices Survey (2005). The use of liquid systems was estimated based on a relationship to farm size, for Eastern and Western Canada respectively, derived from the survey data. Liquid system use increased from 17% in 1990 to 64% in 2011, the most recent survey year, while solid manure is assumed to be inversely related to liquid use. Survey data were used to disaggregate liquid systems into three AWMS sub-systems: earthen basin, tank and slatted floor. A portion of total solid manure is composted, while the remainder is disaggregated into two solid AWMS sub-systems based on survey data: pack and pile. For each liquid subsystem, manure was separated by the presence or absence of crust formation based on data collected from the Livestock Farm Practices Survey compiled in Sheppard et al. (2011a). Lastly, for each liquid and solid subsystem in a given province, manure was further divided based on the use of manure covers during storage.

Swine

For swine, a manure storage time series was developed from a combination of data from the Farm Inputs Management Survey (1995), the Farm Environmental Management Surveys (2001, 2006, 2011) and the Livestock Farm Practices Survey (2005). The use of liquid systems was estimated based on a relationship with farm size and was modelled based on provincial farm sizes from the COA. Liquid system use increased from 80% in 1990 to 97% in 2011, the most recent survey year included, while solid manure was assumed to be inversely related to liquid use. Survey data were used to disaggregate liquid systems into three AWMS sub-systems: earthen basin, tank and slatted floor. Solid manure was disaggregated into two solid AWMS sub-systems: Pack and Pile, based on survey data. For each liquid subsystem, manure was separated by the presence or absence of crust formation based on data collected from the Livestock Farm Practices Survey (Sheppard et al., 2010b). Lastly, for each liquid and solid subsystem in a given province, manure was further divided based on the use of manure covers during storage.

All Other Animals

A survey of experts on the topics of manure management and animal production was conducted in 2003–2004 as part of the Tier 2 study by Marinier et al. (2004). National averages of results are summarized in Table A3.4–15. Briefly, among the dominant animal production categories across the country, poultry manure is stored as solid manure, and beef cattle manure is equally distributed between solid storage and deposition on pasture, with the exception of British Columbia and Manitoba, where the majority of manure is deposited on pasture.

For minor livestock categories where the default IPCC Tier 1 methodology is used to estimate manure management CH₄ emissions, AWMS distributions are reported in CRF tables for consistency with reporting of manure management N₂O emissions (see A3.4.4.1), but are not incorporated in the calculations.

Table A3.4–18 Percentage of Manure Handled by Animal Waste Management Systems (AWMS) for Canada (per Animal Category, Based on the Distribution of Animal Populations in 2020)

Animal Category	Liquid Systems	Solid Storage and Drylot	Pasture, Range and Paddock	Other Systems
Non-Dairy Cattle	5.3	45	45	4.2
Dairy Cattle	64	18	16	2.9
Poultry	7.0	92	0.6	0.6
Sheep and Lambs	0.1	34	66	0.02
Llamas and Alpacas ^a	0.03	28	72	0.02
Swine	97	3	0	0
Goats	0	42	58	0
Horses	0	31	68	0.7
Bison	0.2	46	50	4.0
Deer and Elk ^b	0	47	50	3.5
Fur-bearing Animals ^c	0	100	0	0
Mules and Asses ^d	0	32	68	0.7
Wild Boars ^c	0	100	0	0

Notes:

Totals may not add up to 100% due to rounding.

a. Assumes that manure handled by AWMS is the same for llamas and alpacas as for sheep and lambs, at the provincial level.

b. Identical distributions to non-dairy cattle, except that liquid systems are distributed to pasture, range and paddock (PRP).

c. Assumed 100% solid manure.

d. Assumes that manure handled by AWMS is the same for mules and asses as for horses.

A3.4.3.4. Methane Conversion Factor (MCF)

The MCF describes the proportion of B_0 that is attained, depending on the storage system and climate region. The values published in the 2006 IPCC Guidelines were used for all animals, with the exception of poultry. Where a range of temperature dependent MCFs were available, the value for cool climate and average annual temperature of 12°C was used.

For poultry animals on liquid manure management systems, an MCF that was consistent with all other livestock liquid manure management systems was used, as storage methods for liquid poultry manure in Canada do not differ significantly from storage systems used in dairy or swine production.

For the Dairy Cattle and Swine categories, MCF values from the 2006 IPCC Guidelines were assigned to each AWMS subsystem (section A3.4.3.3). In liquid subsystems, the Liquid/Slurry MCF value of 20% (without crust) or 13% (with crust) was used for Tank and Earthen Basin, while Pit Storage Below Animal Confinements was used for Slatted Floor systems (MCF=20%). For solid subsystems, the Drylot MCF was used for Pack, while the Solid Storage MCF was used for manure heaps. For Dairy Cattle, the Drylot MCF was also used for Exercise Yards. A full list of MCF values by livestock and manure system can be found in Annex 6.4.

A3.4.3.5. Cattle Manure Management CH₄ Emission Factors

Cattle emission factors that are developed to calculate CH₄ emissions from manure management systems vary by animal subcategory and over time (Table A3.4–19). As VS was calculated based on the GE derived from the enteric fermentation cattle production approach, an emission factor time series was derived for cattle to reflect (1) the increase in milk productivity of dairy cows, (2) the variation in overall methane conversion rates as impacted by changes to manure storage practices, and (3) the change in live weight of beef cattle as explained in sections A3.4.1, A3.4.3.4 and A3.4.1.1, respectively. Emission factors are highest from dairy cattle, reflecting their high rates of confinement, use of liquid manure management systems and high dietary intake for sustained milk production. Dairy emission factors have more than doubled since 1990 due to the increasing use of liquid manure management systems. Beef cattle emission factors are lower, reflecting their lower rates of confinement, lower GE and the fact that the majority of manure is managed in a solid form with a low MCF.

Table A3.4-19 Emission Factors to Estimate CH₄ Emissions from Manure Management for Cattle Subcategories from 1990 to 2020

Year	EF _(MMJ) (kg CH ₄ head ⁻¹ yr ⁻¹)							
	Dairy Cows	Dairy Heifers ^a	Bulls	Beef Cows	Beef Heifers	Heifers for Slaughter ^b	Steers ^b	Calves
1990	13	8	4.5	4.1	3.2	1.9	1.8	2.2
1995	15	9	4.7	4.3	3.2	2.0	1.9	2.1
2000	20	11	4.7	4.5	3.3	2.1	1.9	2.3
2005	26	12	4.6	4.3	3.1	2.1	1.9	2.4
2010	33	15	5.0	4.4	3.1	2.1	2.0	2.8
2011	35	16	5.0	4.4	3.1	2.1	2.0	2.9
2012	35	16	5.0	4.4	3.1	2.1	2.0	2.9
2013	36	16	4.5	4.3	3.1	2.1	2.0	2.8
2014	36	17	4.7	4.4	3.1	2.1	2.0	2.9
2015	37	17	4.9	4.5	3.2	2.2	2.0	2.9
2016	37	17	4.9	4.5	3.2	2.2	2.0	2.9
2017	38	17	5.0	4.5	3.2	2.1	2.0	2.9
2018	38	17	4.8	4.5	3.2	2.2	2.0	3.0
2019	39	17	4.8	4.5	3.2	2.2	2.0	3.0
2020	39	17	4.8	4.5	3.2	2.2	2.0	3.0

Notes:

a. For dairy heifers, emission factors were estimated using B₀, MCF and manure management systems for dairy cows.

b. Reported as kg head⁻¹ yr⁻¹, but emissions are calculated based on time to slaughter.

A3.4.3.6. Swine Manure Management CH₄ Emission Factors

Swine emission factors are developed to calculate CH₄ emissions from manure management systems and vary by animal subcategory and over time (Table A3.4–20).

A provincial emission factor time series was derived for swine to reflect (1) the variation in overall methane conversion rates as impacted by changes to manure storage practices, and (2) changes in the growth rates and live weights of market swine by weight class, as explained in sections A3.4.3.4 and A3.4.1.2, respectively. The swine emission factor is first calculated using VS derived from Marinier et al. (2004), and incorporating the latest scientific information available on B₀ and MCF taken from the 2006 IPCC Guidelines (IPCC, 2006). The annual VS excretion rates are then recalculated using animal mass from the Marinier survey year, and expressed as VS per 1000 kg animal mass. Lastly, VS is scaled over time using the swine TAM time series.

Emission factors for pigs in the low-weight and middleweight classes decrease slightly over time due to increases in the rate of weight gain and increases in the methane conversion factor. In contrast, a steady increase in the upper-weight class emission factor reflects increases in live weight. A small decrease in the emission factor for sows over time is the result of proportional changes to provincial animal populations, leading to an overall decrease in VS.

A3.4.3.7. Manure Management CH₄ Emission Factors for All Other Livestock

Manure management system emission factors for animals other than swine and cattle vary by animal subcategory but are constant over time (Table A3.4–21). For the largest other animal categories—sheep and poultry—growth stages for animals are taken into account. Emission factors for sheep, lambs, goat, horses, bison, llamas and alpacas, and poultry are calculated using the 2006 IPCC Tier 2 methodology. VS are derived from Marinier et al. (2004); however, since this report was based on the 2000 IPCC Guidelines, the emission factors were recalculated to incorporate the latest scientific information available on B₀ and MCF taken from the 2006 IPCC Guidelines (IPCC, 2006). Proxies are used for very minor livestock categories that account for less than 0.2% of total agricultural emissions, as described in A3.4.3.

Emission factors for other minor categories tend to be low due to the large portion of manure that is deposited either on pasture, range or paddock or in solid form in pens and holding yards. Default Tier 1 IPCC emission factors from Table 10.15 of Chapter 10 of the 2006 IPCC Guidelines are used for deer and elk, foxes, mink, rabbits, and mules and asses, and represent less than 0.1% of total agricultural emissions.

Table A3.4–20 Emission Factors to Estimate CH₄ Emissions from Manure Management for Swine Subcategories from 1990 to 2020

Year	Boars	Sows	EF _{(MM)T} (kg CH ₄ head ⁻¹ yr ⁻¹)		
			Pigs (< 20 kg)	Pigs (20–60 kg)	Pigs (> 60 kg)
1990	7.0	7.3	2.2	4.5	8.3
1995	7.0	7.2	2.2	4.5	8.4
2000	7.0	7.2	2.2	4.5	8.5
2005	7.0	7.1	2.2	4.4	8.5
2010	7.0	7.0	2.2	4.4	8.7
2011	7.0	7.0	2.1	4.3	8.7
2012	7.0	7.0	2.1	4.3	8.8
2013	7.0	7.0	2.1	4.3	8.9
2014	7.0	7.0	2.1	4.3	8.9
2015	7.0	7.0	2.2	4.3	9.0
2016	7.0	7.0	2.1	4.3	9.1
2017	7.0	7.0	2.1	4.3	9.1
2018	7.0	7.0	2.1	4.3	9.1
2019	7.0	7.0	2.2	4.3	9.2
2020	7.0	7.0	2.2	4.3	9.3

Table A3.4–21 2020 CH₄ Emission Factors for Manure Management for All Other Livestock

Non-Cattle Animal Categories	Manure Management Emission Factors EF _(MM) (kg CH ₄ head ⁻¹ yr ⁻¹)
Other Livestock	
Sheep	
Sheep	0.33
Lambs	0.22
Goats	0.32
Horses	2.6
Bison	2.1
Elk and Deer	0.22
Wild Boars	0.56
Foxes	0.68
Mink	0.68
Rabbits	0.08
Mules and Asses	0.76
Poultry	
Chickens	0.03
Hens	0.12
Turkeys	0.10
Note:	
a. Emission factor based on swine VS, assuming 100% solid manure.	

A3.4.3.8. Verification of Parameter Selection Against Canadian Research

The Manure Management source category was a part of a Tier 2 QA/QC for the Agriculture sector for the 2011 submission (MacDonald and Liang, 2011), including a review and compilation of Canadian literature related to methane production from manure storage.

Few studies have measured emissions from manure storage or quantified the characteristics of manure and manure storage strategies that influence emissions in Canada. Observed emission factors are highly variable, as are measurement techniques. The methodological variability makes comparison of specific parameters used in Tier 2 calculations extremely difficult. When the liquid storage MCF was estimated from in-situ measurements, it varied from greater than 100% (suggesting that B_0 is also underestimated) to as low as 14% in the case of swine, and from 4% to 62% for dairy with no mitigation measures in place (Kaharabata et al., 1998; Massé et al., 2003, 2008; Wagner-Riddle et al., 2006; Laguë et al., 2005; Park et al., 2006, 2010; VanderZaag et al., 2009, 2010). Some studies exist in Canada on emissions from solid manures and other storage methods (composting) (Pattey et al., 2005; Xu et al., 2007; Hao, 2007; Hao et al., 2001b, 2008, 2009, 2010a, 2010b). As was the case with liquid manure systems, variability in emissions and methodology makes comparisons to IPCC parameters difficult.

Godbout et al. (2010) carried out an analysis on a small sample set from Eastern Canadian farms and suggested that the B_0 values for Swine, Non-Dairy Cattle and Dairy Cattle category livestock were 0.47–0.42, 0.21–0.19 and 0.35–0.30 $\text{m}^3 \text{CH}_4 \text{ kg}^{-1} \text{ VS}$, respectively. The values for Non-Dairy Cattle and Swine are consistent with IPCC default values, though dairy manure is the exception, with observed B_0 being 50% higher than the default value. In VanderZaag et al. (2018) B_0 for raw manure from two dairy farms was found to be 0.248 (SD=2) and 0.247 (SD=6). Further analyses of B_0 are required for a wider range of regions and production practices.

Quantities of VS stored in the manure management systems for different animal categories tend to be consistent with quantities estimated in inventory calculations. The variability observed in studies is therefore likely linked to a combination of differences in measurement methodology, variability in manure characteristics (B_0) and differences in a number of physical and biochemical factors for each experimental situation that are not taken into account in the IPCC Tier 2 approach. These factors include temperature, manure composition, storage dimension, storage duration and storage cleaning procedures—all of which may influence emissions from manure storage (Pattey et al., 2005; Laguë et al., 2005; Park et al., 2006, 2010; Wagner-Riddle et al., 2006; Massé et al., 2008; VanderZaag et al., 2009, 2010). Furthermore, these factors are not controlled in research, making comparisons even more difficult. More standardized factorial research is required in order to understand the relative weight of factors that influence emissions from manure storage and to refine estimation methodology.

Based on current research results, no specific bias can be determined in results for manure management systems, as there is no clear standard for evaluating whether IPCC parameters are appropriate for estimating emissions from manure management systems.

Desjardins et al. (2018) measured CH_4 flux for full farm systems, including emissions from both manure management and enteric fermentation processes using an aircraft-based platform and compared top-down estimates with a bottom-up footprint adjusted inventory estimate of emissions for an agricultural region in eastern Ontario, Canada. They concluded that when a wetland area in the flux footprint was less than 10%, the top-down and bottom-up estimates were within the measurement error. They noted, however, that top-down CH_4 fluxes significantly over-estimated CH_4 emissions when contributions from wetlands were not considered in the potential sources. Fine-scale mapping of wetlands was required to effectively quantify natural methane emission sources. Where estimates from the two methods were inconsistent, the discrepancy was related to both increasing fractional area of wetlands in the flux footprint and increasing surface temperature.

A3.4.3.9. Uncertainty in Manure Management CH_4 Emissions

Methane emissions from manure management systems were included in the comprehensive uncertainty analysis discussed in section A3.4.2.4. As was the case with the enteric fermentation process, the analysis built on the recent study by Karimi-Zindashty et al. (2012) and applied a precautionary principle such that for parameters with very little information, probability distributions were intentionally conservative (Table A3.4–22). Data on the probability distributions of the coefficients used in the agricultural manure management IPCC Tier 2 approach are scarce, and expert opinions were the main source of probability distributions, particularly those compiled in the Marinier et al. (2004) report. As was the case with the method for enteric fermentation, the relative uncertainty for the 2012 analysis was applied to the current year and no new uncertainty analysis was carried out for the changes to the methodology for dairy cattle livestock.

Population uncertainty for major animal categories was identical to that discussed in section A3.4.2.3, and the distributions used to define uncertainties can be found in Table A3.4–12.

The parameters used in the calculation of Tier 2 manure management system emission factors for all animals can be divided into two categories: those associated with VS calculation and those specific to the calculation of IPCC Tier 2 emission factors. The confidence intervals assigned to coefficients used in the calculation of volatile solids were relatively small compared to parameters used in the calculation of emission factors. With the exception of the ash content of manure, parameters tend to be under 10%, largely because parameters such as DMI and DE% are values with which producers are very familiar and which can provide some degree of confidence. In the case of cattle, volatile solids vary according to the GE of consumption and are subsequently similar in variability to the enteric fermentation emission factor ($\pm 19\%$).

The probability distributions for coefficients used in IPCC Tier 2 equations used to calculate the emission factors were taken, for the most part, directly from Karimi-Zindashty et al. (2012), who derived the distributions either from expert opinion within the Marinier et al. (2004) report or directly from the 2006 IPCC Guidelines. The uncertainty for B_0 was taken from Marinier et al. (2004), but no reliable source was available for the estimate of uncertainty around the MCF. In the current study, a large uncertainty range was used ($\pm 45\%$ of the mean) based on expert opinions. However, the choice of this value simply indicates that our confidence in the MCF value is low. The actual value of the total uncertainty estimate for manure management systems must therefore be taken within the context that it is highly dependent on a value and a probability distribution function that is highly uncertain.

In contrast with the Karimi-Zindashty (2012) study, the current analysis was based on a provincial distribution of manure management systems, and uncertainty ranges were estimated from values observed in different provincial and national reports (Koroluk and Bourque, 2003; BPR-Infrastructure, 2008) and surveys (Sheppard et al., 2009, 2010, 2011; Sheppard and Bittman, 2011). In the case of dairy cattle livestock, the lower bound for liquid manure management systems was based

Table A3.4-22 Uncertainties in Inputs, Sources of Uncertainty and the Spatial Scale and Animal Category to Which Uncertainty is Assigned, for Parameters Used in Estimating Methane Emissions from Manure Management

Parameter Category	Parameter/Animal Category or Subcategory	Distribution Type	Uncertainty Range		Spatial Allocation/Animal Category Allocation	Uncertainty Distribution Estimate Source and Notes				
			Range	Most Likely Value ^a						
Volatile Solid Calculations (Equation A3.4-6 and A3.4-7)										
Dry Matter Intake (DMI)										
- Swine	Triangular				National/Subcategory	Marinier et al. (2004)				
Boars			1.2–3.4	2.28						
Sows			2.0–2.5	2.25						
Pigs < 20 kg			0.55–0.72	0.68						
Pigs 20–60 kg			0.63–2.1	1.75						
Pigs > 60 kg			2.1–3.3	2.7						
- Poultry										
Laying hens			7.4–9.9	9.85						
Broilers			0.085–0.088	0.086						
Turkeys			0.23–0.53	0.27						
- Other livestock	Triangular				National/Category ^b	Marinier et al. (2004)				
Sheep			1.2–3.0	2						
Lambs			1.2–1.6	1.35						
Goats			1.4–2.3	1.75						
Horses			7.4–9.9	9.85						
Buffalo			6.8–10.1	8.43						
Ash										
- Cattle			3.9–11	8						
- Swine			3.9–11	4.8–5.1						
- Poultry	Laying hens		3.9–11	10						
	Broilers		3.9–11	7						
	Turkeys		3.9–11	5						
- Other livestock	Triangular									
Sheep			3.9–11	8						
Lambs			3.9–11	8						
Goats			3.9–11	8						
Horses			3.9–11	4						
Buffalo			3.9–11	8						

Table A3.4–22 Uncertainties in Inputs, Sources of Uncertainty and the Spatial Scale and Animal Category to Which Uncertainty is Assigned, for Parameters Used in Estimating Methane Emissions from Manure Management (cont'd)

Parameter Category	Parameter/Animal Category or Subcategory	Distribution Type	Uncertainty Range		Spatial Allocation/Animal Category Allocation	Uncertainty Distribution Estimate Source and Notes			
			Range	Most Likely Value ^a					
Digestible Energy (DE)									
-Cattle	Normal		Pasture ±9% / Confined ±9% / Background ±7.5% / Prepared feed ±5.5%		Provincial/Production subcategory	Derived from raw data supplied by Valacta Dairy Services			
-Swine			±9%		Provincial/Category				
-Poultry	Laying hens		±5.5%		National/Subcategory				
	Broilers								
	Turkeys								
-Other livestock									
	Sheep		±9%		Provincial/Category				
	Lambs				Provincial/Category				
	Goats				Provincial/Category				
	Horses				Provincial/Category				
	Buffalo				Provincial/Category				
Emission Factor Calculation (Equation A3.4–5)									
Methane Conversion Factor (MCF)									
	All Animals	Normal	±45%		National	Karimi-Zindashty et al. (2012) – expert opinion			
Maximum Methane Producing Potential (B_0)									
	Dairy cattle	Triangular	0.1–0.24	0.24	National/Category	Karimi-Zindashty et al. (2012) – IPCC (2006)/Marinier et al. (2004)			
	Non-dairy cattle		0.19–0.33	0.19					
	Swine		0.32–0.48	0.48					
	Poultry		0.24–0.39	0.32					
	Sheep and lambs		0.19–0.36	0.19					
	Goats		0.15–0.19	0.18					
	Horses		0.30–0.36	0.3					
	Buffalo		0.19–0.33	0.19					
Animal Waste Management Systems (MS)^d									
	Dairy cattle	Triangular	LB: MLV-10% UB: MLV+25%	MLV from Marinier et al. (2005)	Provincial/Category	Expert opinion, bounds based on interpretation of multiple data sources Internally correlated variable ^c Liquid systems allowed to vary to non-symmetric triangular distributions			
	Swine		LB: MLV-10% UB: 100%	MLV from Marinier et al. (2005)					
	Non-dairy cattle	Normal	±17%			Marinier et al. (2005). Internally correlated variable ^c			
	Poultry								
	Sheep and lambs								
	Goats								
	Horses								
	Buffalo								
Notes:									
MLV = Most likely value; LB = Lower bound; UB = Upper bound									
a. Most likely value when triangular distribution, normal distributions given as simple ±%.									
b. Ash for swine varies among some provinces.									
c. Internal correlation indicates values that vary in terms of a fraction of the whole, i.e., a fraction of a total equalling 100%.									
d. Values that vary independently during trend analysis.									

on a comparison between reports that suggested that manure treated by liquid systems could vary by as much as 10% above or below the Marinier et al. (2005) estimate. Furthermore, it was reported that there has been a continual movement towards liquid manure systems over time. Therefore, the upper bound was set as 25% based on the rate of adoption of liquid systems from BPR-Infrastructure (2008) and the number of years that have passed since the survey by Marinier et al. (2005). In the case of swine animals, liquid manure management systems' upper bounds were fixed at 100%. Other manure management systems' lower bounds for all animal types were 0, also tending to skew probability distributions. This approach resulted in non-symmetrical distributions for all manure management systems. While this approach increased the uncertainty of each individual manure management system, relative to the Karimi-Zindashty study, it likely reduced its impact on the national emission uncertainty because the manure systems were disaggregated to the provincial level, and the total manure management systems were held to 100% of total manure management systems.

The trend analysis carried out using the ECSM quantified the uncertainty in the magnitude of the change in emissions over time for manure management systems. As was the case for the enteric fermentation method, for the long-term trend, emissions for 1990 and 2013 were calculated simultaneously, allowing only time-dependent parameters to vary independently in the estimates. A more detailed description of the trend analysis is found in section A3.4.2.4. The parameters that were allowed to vary independently for the manure management system trend analysis were animal populations, milk production and fat content in dairy cattle animals, body weights in beef cattle and AWMS (noted by a superscript 7 in Table A3.4–12 and superscript 5 in Table A3.4–22). Before 2004, lower boundaries for liquid AWMS were calculated based on the rate of adoption of liquid systems and the number of years that have passed since the survey by Marinier et al. (2005), as in the case of upper boundaries. This approach resulted in non-symmetrical distributions for all manure management systems; and for the trend analysis, it also modified the symmetry of probability distributions around liquid systems between the base year and the current year. Trend uncertainty for the 2018 inventory was based on the 2012 trend analysis.

The summary of results of the uncertainty analysis on emissions reported under Manure Management is reported in Chapter 5. Briefly, the uncertainty range used to derive the uncertainty reported in Chapter 5 for the 2014 emissions from manure management is 60% (-32% to +27% of the mean). As was the case with the enteric fermentation results, emission factors account for the majority of uncertainty. Emission factors lie within an uncertainty range of -34% to +62% for the Non-Dairy Cattle category and a range of -60% to +50% for Dairy Cattle. The emission factors for the Swine category, the largest single contributor to manure management emissions, lie within an uncertainty range of -51% to +43%. All other animals contribute little to the emission totals, i.e., 0.19 Mt CO₂ eq within an uncertainty range of 0.13 (-35% of the mean) to 0.23 (+15% of the mean). Overall, as was the case with enteric fermentation results, mean emissions for both the Dairy Cattle and Non-Dairy Cattle categories estimated using the stochastic model are slightly higher than those calculated from non-stochastic models and tend to be slightly skewed towards the lower boundary, indicating a tendency towards higher emissions. However, mean emissions from swine and other animals estimated using the stochastic model are slightly lower than emissions estimates, and the distribution of emission estimates tends to be slightly skewed towards the upper boundary, indicating a tendency towards lower emissions. This skewed distribution is evident when looking at the range of uncertainty around the emission factors (e.g. 34% to +62% for Non-Dairy Cattle). The asymmetry of the uncertainty range is likely due to a combination of the skewed probability distributions for manure management systems and the same factors that influenced the distribution of enteric fermentation emission estimates for cattle, specifically the skewed distributions for backgrounding of slaughter animals and the uniform distribution used for net energy mobilized from weight loss during lactation in Dairy Cattle.

Based on the trend analysis, there has been no detectable increase in emissions from manure management since 1990, where change from 1990 could range from a decrease of 10% to an increase of 8%, though it is most likely that there has been an increase in emissions of roughly 5.5%. The assumption that liquid manure storage and other manure storages have increased over time affects the trend. For example, for dairy cattle livestock in Ontario in 1990, the triangular distribution used around the percentage of manure treated in liquid manure management systems had a lower boundary of 16%, a MLV of 40% and an upper boundary of 42%; in 2010, the lower boundary was 37%, the MLV was 40% and the upper boundary 59%. The use of a skewed distribution indicating a higher probability that fewer animals were raised on liquid manure management systems in the past balances the increase in animal populations. As a result, it is improbable overall that there is an increase in manure management emissions over time, particularly from cattle.

The uncertainty range of the analysis carried out in 2012 was slightly smaller than that of the previous analysis (2%), likely due to a combination of lower uncertainty for census animal populations and modifications in the uncertainty bounds around AWMS systems with the addition of two years from the time of the original survey. Overall, the uncertainty range around manure management emissions produced by this analysis is slightly smaller than the data reported by Karimi-Zindashty et al. (2012), as the proportions of manure treated by different manure management systems were distributed to the provincial level in this analysis, whereas a national average was used in the 2012 publication. Monni et al. (2007) estimated CH₄ manure management emission factor uncertainty to be roughly ±30% based strictly on expert opinion. As was the case with enteric fermentation, Karimi-Zindashty et al. (2012) demonstrated that most uncertainty in the manure management quantification approach is associated with the use of default IPCC parameters that are applied at the national

level, specifically the MCF. By deriving MCF factors for different regions and different storage structures, uncertainty would be significantly reduced. Further work on uncertainty will focus on the development of trend uncertainty and the refinement of probability distributions around country-specific parameters already existing in the approach. As the MCF factor is driving uncertainty for the Manure Management category, it is not suspected that changes to the dairy or swine methodologies would have a large impact on the national manure management uncertainty. However, the introduction of a time series of AWMS for the Dairy and Swine sectors may play an important role in influencing the trend uncertainty for manure management system emissions.

A3.4.4. N₂O Emissions from Manure Management

N₂O emissions from manure management systems result from mineralization of organic materials, and the nitrification and denitrification of mineral N directly and indirectly.

A3.4.4.1. Direct N₂O Emissions from Manure Management

Three factors are required to estimate N₂O emissions from manure management systems using the IPCC Tier 1 method: (1) N excretion rates for various animal categories and subcategories, (2) types of AWMS and (3) emission factors associated with manure management systems.

As previously described in section A3.4.3, default emission factors or country-specific information sources are sometimes used for minor livestock categories as logical proxies based on species similarities when no other information is available. The following proxies and expert judgement are used in the calculation of N₂O emissions, in addition to those already listed in A3.4.3:

- The N excretion rate for Swine is used to represent wild boars.
- The N excretion rate for Sheep is used to represent lambs, as well as llamas and alpacas.
- The N excretion rate for Buffalo is used to represent bison.
- The N excretion rate for Other Cattle is used to represent Deer and Elk.

Nitrogen Excretion Rates for Various Domestic Animals

For the Dairy Cattle category, the Tier 2 methodology from the 2006 IPCC Guidelines is used. Nitrogen retention from milk production and weight gain is calculated from Equation 10.33 in Volume 4, Chapter 10 of the 2006 IPCC Guidelines. Nitrogen retention from pregnancy was also estimated using a country-specific approach. The weight gain rate of the fetus was estimated assuming the average weight of a calf at birth to be 40 kg (Farm & Food Care Ontario, 2013) and gestation period of 276 days. The N retention due to fetus growth of a pregnant cow was then weighted to 365 days to account for its contribution in the annual N excretion rate. Nitrogen intake from feed has increased steadily since 1990 in order to meet the protein requirements of increased milk production (Table A3.4–4) and, as a result, a corresponding increase in dairy cow N excretion rates (Table A3.4–23) was calculated.

For the Non-Dairy Cattle category, annual live weights (see section A3.4.1.1) were multiplied by the IPCC default N excretion rate (IPCC, 2006) to produce a time series of manure N excretion rates (Table A3.4–23).

For the Swine category, distinct parameters were used to estimate N excretion from subcategories of breeding animals and market animals. In the case of market swine, increases in growth rates and live weights were used to develop a country-specific time series of animal mass per production stage, which was multiplied by the N excretion rate from Table 10.19 in the 2006 IPCC Guidelines. For breeding animals, the IPCC default N excretion rate was multiplied by the IPCC default animal mass.

Annual manure N excretion rates for all other types of animals vary by livestock category according to IPCC Tier 1 default values (IPCC, 2006). Poultry have high excretion rates (Table A3.4–25), while horses and bison have the lowest excretion rates. However, on a per-head basis, bison have the highest N excretion rates due to their size. Tier 1 default values for fur-bearing animals and rabbits have exceptionally high excretion rates relative to their size (Table A3.4–25), but are understood to be based on breeding stock and attribute all manure produced on the farm to the breeding stock.

Table A3.4–23 Time Series of Manure N Excretion Rates for Cattle (kg N head⁻¹ yr⁻¹)

Year	(kg N head ⁻¹ yr ⁻¹)								
	Dairy Cows	Dairy Heifers	Bulls	Beef Cows	Beef Heifers	Heifers for Slaughter ^a	Steers ^a	Calves	
1990	107	72	88	58	45	45	48	27	
1995	110	72	99	65	50	55	57	27	
2000	114	73	103	70	54	60	61	27	
2005	116	73	102	68	52	61	61	26	
2010	123	76	113	69	53	62	63	27	
2011	122	76	112	69	53	62	64	27	
2012	122	76	114	69	53	65	65	27	
2013	126	76	99	69	53	64	65	27	
2014	125	76	103	70	53	63	64	27	
2015	123	76	111	74	56	65	66	27	
2016	123	76	112	75	58	66	67	27	
2017	121	76	114	75	57	65	66	26	
2018	122	76	108	75	57	66	67	26	
2019	122	76	107	74	57	66	68	26	
2020	122	75	107	75	57	67	68	26	

Notes:

N excretion rate for non-dairy cattle is 0.31 kg N (1000 kg⁻¹ day⁻¹) (IPCC, 2006, Table 10.19).

Data source = IPCC (2006), Volume 4, Agriculture, Forestry and Other Land Use.

a. Values are adjusted for the life-span of slaughter animals.

Table A3.4–24 Time Series of Manure N Excretion Rates for Swine (kg N head⁻¹ yr⁻¹)

Year	(kg N head ⁻¹ yr ⁻¹)								
	Sows	Boars	Pigs (<20 kg)	Pigs (20–60 kg)	Pigs (>60 kg)				
1990	17	17	1.3	5.7	11.9				
1995	17	17	1.3	5.8	12.1				
2000	17	17	1.3	5.7	12.4				
2005	17	17	1.3	5.7	12.4				
2010	17	17	1.3	5.7	12.8				
2011	17	17	1.3	5.6	12.9				
2012	17	17	1.3	5.7	13.0				
2013	17	17	1.3	5.6	13.0				
2014	17	17	1.3	5.7	13.2				
2015	17	17	1.3	5.6	13.2				
2016	17	17	1.3	5.6	13.4				
2017	17	17	1.3	5.6	13.4				
2018	17	17	1.3	5.6	13.5				
2019	17	17	1.3	5.6	13.6				
2020	17	17	1.3	5.6	13.7				

Notes:

The N excretion rates for breeding swine and market swine are taken from the latest version of Volume 4, Chapter 10 of the 2006 IPCC Guidelines, Table 10.19, in units of kg N (1000 kg body weight)⁻¹ day⁻¹. Data source: IPCC (2006), Volume 4, Agriculture, Forestry and Other Land Use.

Table A3.4–25 Manure N Excretion Rates for All Other Animals

Animal Categories	N Excretion Rate ^a (kg N 1000 kg ⁻¹ day ⁻¹)	Average Body Weight ^b (kg)	Annual Manure N (kg N head ⁻¹ yr ⁻¹)
Sheep	0.42	27	4.1
Lambs	0.42	27	4.1
Goats	0.45	64	10.5
Horses	0.3	450	49.3
Llamas and Alpacas	0.42	112	17.2
Bison	0.32	580	67.7
Hens	0.83	1.8	0.5
Broilers	1.1	0.9	0.4
Turkeys	0.74	6.8	1.8
Elk and Deer	0.31	120	13.6
Wild Boars ^c	0.40	61	11.1
Foxes	12.1	1.8	7.9
Mink	4.6	1.8	3.0
Rabbits	8.1	1.6	4.7
Mules and Asses	0.3	245	26.8

Notes:

a. Data source: IPCC (2006).

b. For buffalo, average live weight was taken from the U.S. NIR.

c. Equivalent to overall swine excretion rate of 0.40 kg N (1000 kg⁻¹ day⁻¹) (IPCC, 2006, Table 10.19). Data source: IPCC (2006), Volume 4, Agriculture, Forestry and Other Land Use.

Emission Factors Associated with AWMS

The type of AWMS has a significant impact on N₂O emissions. Less-aerated systems, such as liquid systems, generate little N₂O, whereas drylots produce more. However, there is little scientific information in Canada specifying amounts of N₂O emissions associated with manure management systems. Therefore, IPCC default emission factors, as listed in Annex 6, were used to estimate emissions. For livestock from the Dairy and Swine sectors, weighted N₂O emission factors are calculated using the proportion of manure in each AWMS subsystem (see section A3.4.3.3) and the corresponding default emission factors (Annex 6), to produce a time series of N₂O emission factors by AWMS.

Table A3.4–18 summarizes the distribution of manure management systems in Canada by animal category. N₂O emissions from manure on pasture, range and paddock systems are not included under the Manure Management category, as they are reported under the Agricultural Soils category (section A3.4.5.1). Animal population data are detailed in section A3.4.1.

Direct N₂O emissions from manure management are estimated using the IPCC Tier-1 method (Equation A3.4–9), as follows:

Equation A3.4–9

$$N_2O_{D(mm)} = \sum_i \sum_{AWMS} (N_{i,T} \times N_{i,AWMS} \times N_{EX,T}) \times EF_{AWMS} \times \frac{44}{28}$$

$N_2O_{D(mm)}$	=	emissions for all AWMS and livestock categories, excluding emissions from urine and dung deposited on pasture, range and paddock, kg N ₂ O yr ⁻¹
$N_{i,T}$	=	population for the T th animal category or subcategory in province i
$N_{i,AWMS}$	=	percentage of manure N handled by each AWMS in province i , fraction (see Table A3.4–18)
$N_{EX,T}$	=	N excretion rate for the T th animal category or subcategory (see Table A3.4–23 for cattle and Table A3.4–25 for non-cattle), kg N head ⁻¹ yr ⁻¹
EF_{AWMS}	=	N ₂ O emission factors from manure management for each specific AWMS (see Annex 6), kg N ₂ O-N kg N ⁻¹
44/28	=	coefficient converting N ₂ O-N to N ₂ O

A3.4.4.2. Indirect N₂O Emissions from Manure Management

During animal manure storage and handling, losses of N occur through the following indirect pathways: (1) volatilization of manure N as NH₃ and NO_x and subsequent re-deposition and (2) leaching and runoff of N. Leaching is estimated only for the Dairy and Swine sectors, where country-specific information on the fraction of N loss due to leaching and runoff was available. These losses of manure N can result in N₂O emissions (Equation A3.4–10 and Equation A3.4–11).

In the case of the Dairy and Swine sectors, the introduction of a manure management time series that considered a wider variety of manure storage conditions results in changes in the fraction of manure N that is lost over the reporting period (Table A3.4–27). A shift from solid manure storage to liquid, an increase in the number of covered manure storage systems and, in the case of the Dairy sector, a shift in time in pasture, resulted in a decrease in the proportion of total N lost to the environment over time.

Equation A3.4–10

$$N_2O_{G(mm)} = \sum_i \sum_{AWMS} (N_{i,T} \times N_{i,AWMS} \times N_{EX,T} \times Frac_{GasMS(T,AWMS)}) \times EF_4 \times \frac{44}{28}$$

$N_2O_{G(mm)}$	=	indirect N_2O emissions due to NH_3 volatilization for managed manure, excluding emissions from urine and dung deposited on pasture, range and paddock, kg N_2O yr ⁻¹
$N_{i,T}$	=	population for livestock category or subcategory, T in province i
$N_{i,AWMS}$	=	percentage of manure N handled by each AWMS in province i , fraction (see Table A3.4–18)
$N_{EX,T}$	=	N excretion rate for livestock category or subcategory, T (see Table A3.4–23 for cattle and Table A3.4–25 for non-cattle), kg N head ⁻¹ yr ⁻¹
$Frac_{GasMS(T,AWMS)}$	=	fraction of managed manure N for livestock category, T that volatilizes as NH_3 and NO_x in the manure management system, AWMS (see Table A3.4–27 and Table A3.4–28)
EF_4	=	emission factor from atmospheric deposition of N (see Table A3.4–26)
$44/28$	=	coefficient converting N_2O -N to N_2O

Equation A3.4–11

$$N_2O_{L(mm)} = \sum_i \sum_{AWMS} (N_{i,T} \times N_{i,AWMS} \times N_{EX,T} \times Frac_{LeachMS(T,AWMS)}) \times EF_5 \times \frac{44}{28}$$

$N_2O_{L(mm)}$	=	indirect N_2O emissions due to leaching and runoff from managed manure, excluding emissions from urine and dung deposited on pasture, range and paddock, kg N_2O yr ⁻¹
$N_{i,T}$	=	population for livestock category or subcategory, T in province i
$N_{i,AWMS}$	=	percentage of manure N handled by each AWMS in province i , fraction (see Table A3.4–18)
$N_{EX,T}$	=	N excretion rate for livestock category or subcategory, T (see Table A3.4–23 for cattle, Table A3.4–24 for swine, and Table A3.4–25 for all other livestock), kg N head ⁻¹ yr ⁻¹
$Frac_{LeachMS(T,AWMS)}$	=	fraction of managed manure N losses for dairy (see Table A3.4–28) and swine (see Table A3.4–29) and other livestock (see Table A3.4–27) for livestock category T due to leaching and runoff during solid and liquid storage of manure, AWMS
EF_5	=	emission factor from N leaching and runoff, 0.0075 kg N_2O -N (kg N leaching/runoff) ⁻¹ (IPCC, 2006)
$44/28$	=	coefficient converting N_2O -N to N_2O

Table A3.4–26 Implementation of EF_4 from the 2019 Refinement to the 2006 IPCC Guidelines, by Ecozone

Ecozone	EF_4 kg N_2O -N (kg NH_3 -N + NO_x -N volatilized) ⁻¹
Taiga Plains	0.005
Boreal Shield	0.014
Atlantic Maritime	0.014
Mixedwood Plains	0.014
Boreal Plains	0.005
Prairies	0.005
Pacific Maritime	0.014
Montane Cordillera	0.005

Notes:

- a. Ecozones represent one level within Canada's National Ecological Framework.
- b. Values taken from Table 11.3 of the 2019 Refinement to the 2006 IPCC Guidelines, Volume 4, Chapter 11.

Table A3.4–27 Total N, NH₃- and NO_x-N Losses Associated with Various Livestock and Manure Management Systems

Animal Category	Manure Management Systems	Frac(LossMS) (%) ^a	NH ₃ -N and NO _x -N Loss (%) ^{a, b, c} (Frac _{GasMS})
Non-Dairy Cattle	Liquid	40 (15–45)	40 (15–45)
	Solid Storage	40 (20–50)	30 (20–50)
	Pasture and Range	-	20 (5–50)
Sheep, Lamb, Llamas and Alpacas	Solid Storage	15 (5–20)	12 (5–20)
	Pasture and Range	-	20 (5–50)
Goat and Horse	Solid Storage	15 (5–20)	12 (5–20)
	Pasture and Range	-	20 (5–50)
Elk and Deer	Solid Storage	15 (5–20)	12 (5–20)
Wild Boars	Solid Storage	15 (5–20)	12 (5–20)
Foxes	Solid Storage	15 (5–20)	12 (5–20)
Mink	Solid Storage	15 (5–20)	12 (5–20)
Rabbits	Solid Storage	15 (5–20)	12 (5–20)
Mules and Asses	Solid Storage	15 (5–20)	12 (5–20)
Poultry	Liquid	50	50
	Solid Storage	53 (20–80)	48 (10–60)
	Pasture and Range	-	20 (5–50)

Notes:

a. Numbers in parentheses indicate a range.

b. Data sources: Hutchings et al. (2001); U.S. EPA (2004); Rotz (2004).

c. Leaching loss from pasture, range and paddock is reported under indirect N₂O emissions from agricultural soils and is calculated using the same parameters as manure N spread to agricultural soils.**Table A3.4–28 Total N, NH₃- and NO_x-N Losses Associated with Dairy Cattle and Manure Management Systems**

Year	Frac _(LossMS) (%)			Leaching Loss (%) (Frac _{LeachMS})			NH ₃ -N and NO _x -N Loss (%) (Frac _{GasMS})		
	Liquid	Solid	Other ^a	Liquid	Solid	Other	Liquid	Solid	Other
1990	12	23	0	0	3	0	11	16	0
1995	12	23	0	0	3	0	11	16	0
2000	13	23	0	0	3	0	11	16	0
2005	13	23	37	0	3	7	12	16	23
2010	10	23	35	0	3	5	9	17	24
2015	10	23	35	0	3	5	8	17	24
2016	10	23	35	0	3	5	8	17	24
2017	10	23	35	0	3	5	8	17	24
2018	10	23	35	0	3	5	8	17	24
2019	10	23	35	0	3	5	8	17	24
2020	10	23	36	0	3	5	9	17	24

Note:

a. Other in the case of Dairy Cattle refers only to composting of solid manures.

Table A3.4–29 Total N, NH₃- and NO_x-N Losses Associated with Swine Manure Management Systems

Year	Frac _(LossMS) (%)		Leaching Loss (%) (Frac _{LeachMS})		NH ₃ -N and NO _x -N Loss (%) (Frac _{GasMS})	
	Liquid	Solid	Liquid	Solid	Liquid	Solid
1990	22	31	0	3.3	21	23
1995	23	31	0	3.3	21	23
2000	23	31	0	3.4	21	23
2005	23	31	0	3.3	21	23
2010	20	30	0	3.1	19	23
2015	20	30	0	2.9	18	23
2016	20	30	0	2.9	18	23
2017	20	30	0	2.9	18	23
2018	20	30	0	2.9	18	23
2019	20	30	0	2.9	18	23
2020	20	30	0	2.9	18	23

A3.4.5. N₂O Emissions from Agricultural Soils

Emissions of N₂O from agricultural soils consist of direct and indirect emissions. N₂O emissions that result from anthropogenic N inputs occur through direct pathways, i.e., from the soils to which the N is added, and indirect pathways through (1) volatilization of inorganic N fertilizers and manure N as NH₃ and NO_x and subsequent deposition, and (2) leaching and runoff of N.

Nitrogen is allocated to the landscape according to the following procedure: (1) region-specific N application rates are calculated for each crop type; (2) a “recommended” amount of N is allocated to each of 405 ecodistricts in Canada based on the application rate and the area of each crop type within the ecodistrict; (3) the total amount of manure N available to be applied to agricultural soils is calculated based on the population of livestock within the ecodistrict; (4) biosolids are applied to select crop types according to remaining “recommended” N, after subtracting the available manure N from step 3; (5) manure N is applied to crops in each ecodistrict, according to remaining crop requirements following biosolids application; (6) the amount of organic N applied (manure + biosolids) is subtracted from the initial “recommended” amount to calculate the amount of “theoretical” crop N requirements not met by organic sources alone; and (7) the amount of “theoretical” N is scaled to match total provincial fertilizer sales reported by Statistics Canada, and this corrected amount represents inorganic N fertilizer applied to each ecodistrict.

A3.4.5.1. Direct N₂O Emissions from Agricultural Soils

Direct sources of emissions from agricultural soils include inorganic N fertilizers, organic N fertilizers, urine and dung deposited on pasture, range and paddock by grazing animals, crop residues, mineralization associated with loss of soil organic matter and cultivation of organic soils. Tillage practices and irrigation can also influence soil N₂O emissions. The N₂O emission factors for most of the direct emission sources are country-specific and incorporate the influence of moisture regimes, landscape position, soil texture, cropping systems and N sources on rates of N₂O production and emission. The methodology follows the approach described in Liang et al. (2020), with modifications based on expert consultation with the Canadian scientific community where noted in A3.4.5.1.

The approach involves determining base emission factors “EF_{Base}” for each of 405 ecodistricts,²² using long-term growing season precipitation. The EF_{Base} is subsequently modified to reflect site-specific practices and conditions. Data on long-term climate normals and topographic characteristics are used to develop an EF_{Base} (Equation A3.4–12).

²² “Ecodistrict” represents one level within Canada’s National Ecological Framework. The country includes 1027 ecodistricts, characterized by a distinctive assemblage of relief, landforms, geology, soil, vegetation, water bodies and fauna.

$$EF_Base_i = [EF_CT_{i,P=PE} \times FR_Topo_i + EF_CT_{i,P} \times (1 - FR_Topo_i)] \times RF_TX_i$$

EF_Base_i	=	a weighted average of emission factors for ecodistrict i , taking into account moisture regimes, topographic conditions, and soil texture, kg N ₂ O-N kg N ⁻¹ yr ⁻¹
$EF_CT_{i,P}$	=	emission factor, estimated at actual P in ecodistrict i , kg N ₂ O-N kg N ⁻¹ (see Figure A3.4-4)
$EF_CT_{i,P=PE}$	=	emission factor, estimated at $P=PE$ in ecodistrict i , kg N ₂ O-N kg N ⁻¹
FR_Topo_i	=	fraction of the area of ecodistrict i that is in the lower section of the toposequence (See Liang et al., 2020)
P	=	long-term mean precipitation from May 1 to October 31 for ecodistrict i , mm
PE	=	long-term mean potential evapotranspiration from May 1 to October 31 for ecodistrict i , mm
RF_TX_i	=	weighted soil texture ratio factor of N ₂ O for ecodistrict " i "

Base N₂O Emission Factor (EF_Base)

Soil N₂O is produced mainly during denitrification and is therefore greatly influenced by soil oxygen status. Accordingly, in moisture-limited conditions, N₂O emission factors have been shown to increase with increased rainfall (Dobbie et al., 1999) and climate-variable emission factors have been used in estimating soil N₂O inventory (Flynn et al., 2005). Similarly, this methodology estimates emission factors at the ecodistrict level as a function of the long-term growing season precipitation (P) from May 1 to October 31 (Figure A3.4-4). There are 958 weather stations in the AAFC-archived weather database.²³ These stations (80°00'N–41°55'N, 139°08'W–52°40'W) located across Canada (758 stations) and the United States (200 stations) were used to interpolate precipitation and potential evapotranspiration from May to October from 1971 to 2000 to the ecodistrict centroids. The Meteorological Service of Canada, Environment and Climate Change Canada (ECCC) provided the Canadian weather data.

The EF_Base factors were determined using the same approach as for the determination of the IPCC Tier 1 emission factor by Bouwman (1996), i.e., EF_Base = slope of the "N₂O emissions versus N fertilizer rate" relationship. The EF_CT was derived from an approach developed based on a meta-analysis of recent Canadian studies (Rochette et al., 2018). The method assumes an exponential relationship between emission factors and growing season precipitation.

To account for a topographical effect, a separate EF_CT emission factor was calculated at P=PE (long-term potential evapotranspiration from May to October) for the lower sections of the landscapes (Liang et al., 2020). The fraction of the landscape to which this condition was applied differs among landscape types. Landscape segmentation data were incorporated into the calculation of the national N₂O emission estimates, based on the observations that N₂O emissions are greater in lower sections of the landscape, where intermittently saturated soil conditions are favourable to denitrification (Corre et al., 1996, 1999; Pennock and Corre, 2001; Izaurrealde et al., 2004). The fraction of the landscape occupied by such lower sections (FR_Topo) was applied to concave portions of the landscape (i.e., lower and depressional landscape positions) where soils are likely to be saturated for significant periods of time on a regular basis and where they are imperfectly and poorly drained with mottles²⁴ within 50 cm of the land surface. MacMillan and Pettapiece (2000) used digital elevation models to characterize the areal extent of upper, mid, lower and depressional portions of the landscape and their associated characteristics (slope and length). Their results were used to determine the proportional distribution of different landforms (such as lower sections) in the Soil Landscapes of Canada (SLC), which was the basis for determining the proportion of the landscape to which FR_Topo would be applied to derive N₂O emission estimates (Rochette et al., 2008).

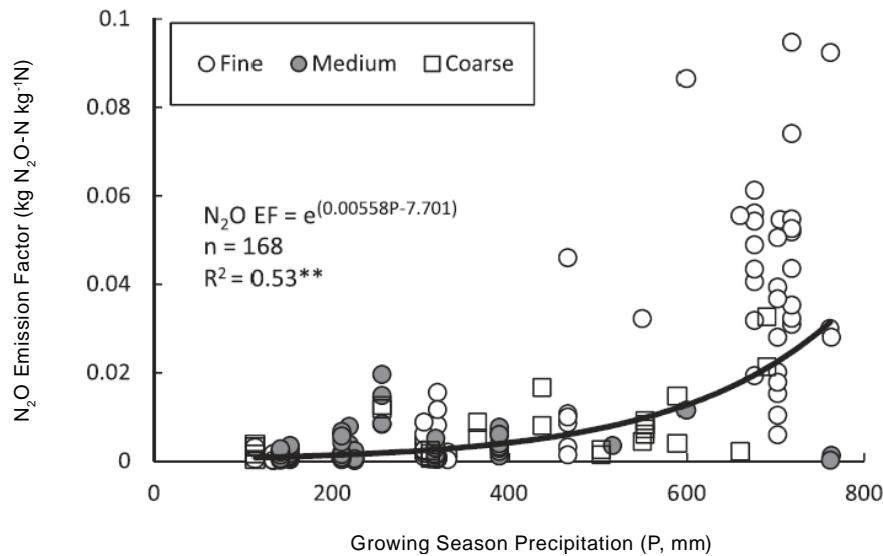
Non-Growing Season N₂O Emissions

Field measurements of N₂O flux using chambers in Eastern Canada are usually made during the snow-free period (Gregorich et al., 2005). Average annual snowfall in Eastern Canada varies between 1.0 and 4.5 m (Environment Canada, 2002). Snowmelt water in the spring creates wet soil conditions that often stimulate N₂O production (Grant and Pattey, 1999; Wagner-Riddle and Thurtell, 1998). The intensity of soil freezing was also found to influence spring thaw emissions (Wagner-Riddle et al., 2007). Limiting emission estimates to the snow-free period therefore underestimates total annual N₂O emissions in that region. Emissions of N₂O during spring thaw also occur on the Prairies, but are usually lower than in Eastern Canada (Lemke et al., 1999). Pelster et al. (2021) compiled all published and unpublished data that compared the

23 Gameda S. Personal communication, AAFC (2006).

24 Mottles are the product of intermittent oxidation/reduction cycles of (generally) iron present in the soil profile. Prevalence, size and colour of mottles are indicative of the soil materials being intermittently saturated for significant periods.

Figure A3.4–4 EF_CT as a Function of Long-Term Growing Season Precipitation (P)



non-growing season soil N₂O fluxes with the growing season, and reported an overall mean of 63.4% of soil N₂O emissions that occurred during the growing season in Canada (manuscript in preparation). A ratio factor (RF_NSE) of 1/0.634 was therefore used to modify the EF_Base to estimate annual emissions.

Soil Texture and N₂O Emissions

Soil texture does not directly influence N₂O production in soils; however, it correlates with several physical and chemical parameters that control N₂O production and transport in the soil profile (Arrouays et al., 2006; da Sylva and Kay, 1997; Minasny et al., 1999). Consequently, soil texture-related variables often correlate with N₂O emissions from agricultural soils (Hénault et al., 1998; Corre et al., 1999; Chadwick et al., 1999; Bouwman et al., 2002a; Freibauer, 2003).

The impact of soil texture on N₂O emissions from agricultural soils was incorporated in the emission factor using a ratio factor (RF_TX) defined as the ratio of N₂O emissions on soils of a given textural class to the mean emissions from soils of all textures (Equation A3.4–13). Liang et al. (2020) reported an RF_TX of 0.49 for coarse and medium textured soils, and 2.55 for fine-textured soil. Based on a recent publication with long-term micro-meteorological data on medium-textured site in southern Ontario (Baral et al. in press) and a scientific review by AAFC scientists, the approach was modified to apply ratio factors of 0.49, 1.0, and 2.55 nationally to coarse, medium and fine textured soils, respectively, as it was determined that the diversity of medium textured soils was not fully represented in the literature data.

Equation A3.4–13

$$RF_TX_i = \sum_j (RF_TX_j \times FR_TX_{i,j})$$

RF_TX_i = weighted soil texture ratio factor of N₂O for ecodistrict "i"

RF_TX_j = ratio factor of N₂O for soil texture "j" (i.e. coarse, medium or fine), for ecodistrict "i"

$FR_TX_{i,j}$ = fraction of soil texture "j" in ecodistrict "i"

Table A3.4–30 Soil N₂O Ratio Factors for Cropping Systems and Nitrogen Sources

Cropping System (CS)	RF_CS ^a	Nitrogen Source (NS)	RF_NS ^a
Annual	1.00	Inorganic Fertilizer N (IN)	1.00
Annual	1.00	Organic Fertilizer N (ON)	0.84
Annual	1.00	Crop Residue N (CN)	0.84 ^b
Perennial	0.19	Inorganic Fertilizer N (IN)	1.00
Perennial	0.19	Organic Fertilizer N (ON)	1.00
Perennial	0.19	Crop Residue N (CN)	1.00

Notes:

a. Source = Liang et al. (2020), except where noted

b. Modified based on expert consultation

Organic Nitrogen Fertilizers

Soil N₂O emissions from organic N sources include emissions from the application of sewage sludge (biosolids), manure from drylot and solid storage, liquid and other waste management systems on agricultural soils. A Tier 2 methodology with country-specific emission factors was used for estimating N₂O emissions from organic N fertilizers.

Equation A3.4–14

$$N_2O_{ON} = \sum [F_{ON(i,m)} \times (EF_Base_i \times RF_NSE \times RF_NS_{k=ON,m} \times RF_CS_m)] \times 44/28$$

N_2O_{ON}	=	emissions from organic N fertilizer applied to cropland, kg N ₂ O yr ⁻¹
$F_{ON(i,m)}$	=	organic N (i.e. biosolids, animal manure) applied as N fertilizer in ecodistrict i, for each cropping system m as shown in Table A3.4–30, in units of kg N yr ⁻¹
EF_Base_i	=	the weighted average emission factor for ecodistrict i described in Equation A3.4–12, kg N ₂ O-N kg N yr ⁻¹
RF_NSE	=	ratio factor of 1/0.634 for the non-growing season soil N ₂ O emissions, unitless
$RF_NS_{k=ON,m}$	=	ratio factor for source of N, for organic N source k=ON in cropping system m as shown in Table A3.4–30, unitless
RF_CS_m	=	a ratio factor for cropping system (annual or perennial) as shown in Table A3.4–30, unitless
$44/28$	=	coefficient converting N ₂ O-N to N ₂ O

Manure Nitrogen

The methodology is based on the quantity of manure N produced by domestic animals (see section A3.4.4.1) and country-specific EF_Base, taking into account the moisture regime and topographic conditions at the ecodistrict level. Manure was allocated to crops preferentially, based on a modified version of Yang et al. (2011), in order to better reflect practices and to ensure consistency in Canada's manure allocation methodology used in environmental indicators in Canada. Estimates of N₂O emissions from this source are calculated using Equation A3.4–14, in combination with other organic N sources.

The amount of animal manure applied as fertilizer at an ecodistrict level was calculated using Equation A3.4–15. It was assumed that all manure, excluding that deposited on PRP, is applied to cropland soils.

Equation A3.4–15

$$F_{ON=MN,i} = \sum_i (N_{T,i} \times N_{EX(T)}) \times (1 - N_{PRP(T)}) \times (1 - FRAC_{LossMS(T,i)})$$

$F_{ON=MN,i}$	=	animal manure nitrogen (MN) applied to agricultural soils as organic N fertilizer in ecodistrict i, kg N yr ⁻¹
$N_{T,i}$	=	population for animal category or subcategory T in ecodistrict i, heads
$N_{EX(T)}$	=	N excretion rate for animal category or subcategory (tables A3.4–23 to A3.4–25)
$N_{PRP(T)}$	=	fraction of manure N on pasture, range and paddock for each animal category or subcategory T in province p (see Table A3.4–18)
$FRAC_{LossMS(T,i)}$	=	fraction of manure N loss during storage and handling (volatilization, leaching, etc.) for each animal category or subcategory T excluding pasture, range and paddock, in ecodistrict i (tables A3.4–27, A3.4–28 and A3.4–29)

Animal population data sources are detailed in section A3.4.1. Annual livestock population data from each animal category or subcategory at the provincial level are disaggregated into ecodistricts based on the livestock population distribution reported from the COA. Between two consecutive census years, livestock population proportions at the ecodistrict level are interpolated.

Biosolids Nitrogen

Data on the production and management of biosolids were derived from an Environment Canada–commissioned report (Cheminfo Services Inc., 2017). The data set was generated through a combination of telephone surveys and reports by the municipal wastewater treatment services in 33 Census Metropolitan Areas (CMAs) and from municipal and provincial environment departments/ministries across Canada. This survey represented only 63% of the Canadian population based on the wastewater treatment plants (WWTPs) located in CMAs and did not include PEI and the three Canadian territories. The data were compiled at five-year intervals (1990–2015) and had gaps and inconsistencies owing to a lack of complete management information and changes in provincial regulations on biosolids. Nevertheless, these data are the only known source for a quantitative analysis of biosolids available at a national scale.

Biosolids production data were produced through a series of analytical steps (Figure A3.4–5, Table A3.4–31). First, a provincial-level per capita methodology was constructed to establish a “baseline biosolids production.” Production was assumed to be directly proportional to the population of a geographical area. Different spatially scaled roll-ups of Statistics Canada population estimates were evaluated for best fit of the data. Population estimates used for testing included CMA

Figure A3.4–5 Schematic Details of the Procedures and Data Sources Used to Determine the Time Series of Biosolids Production at a Provincial Scale

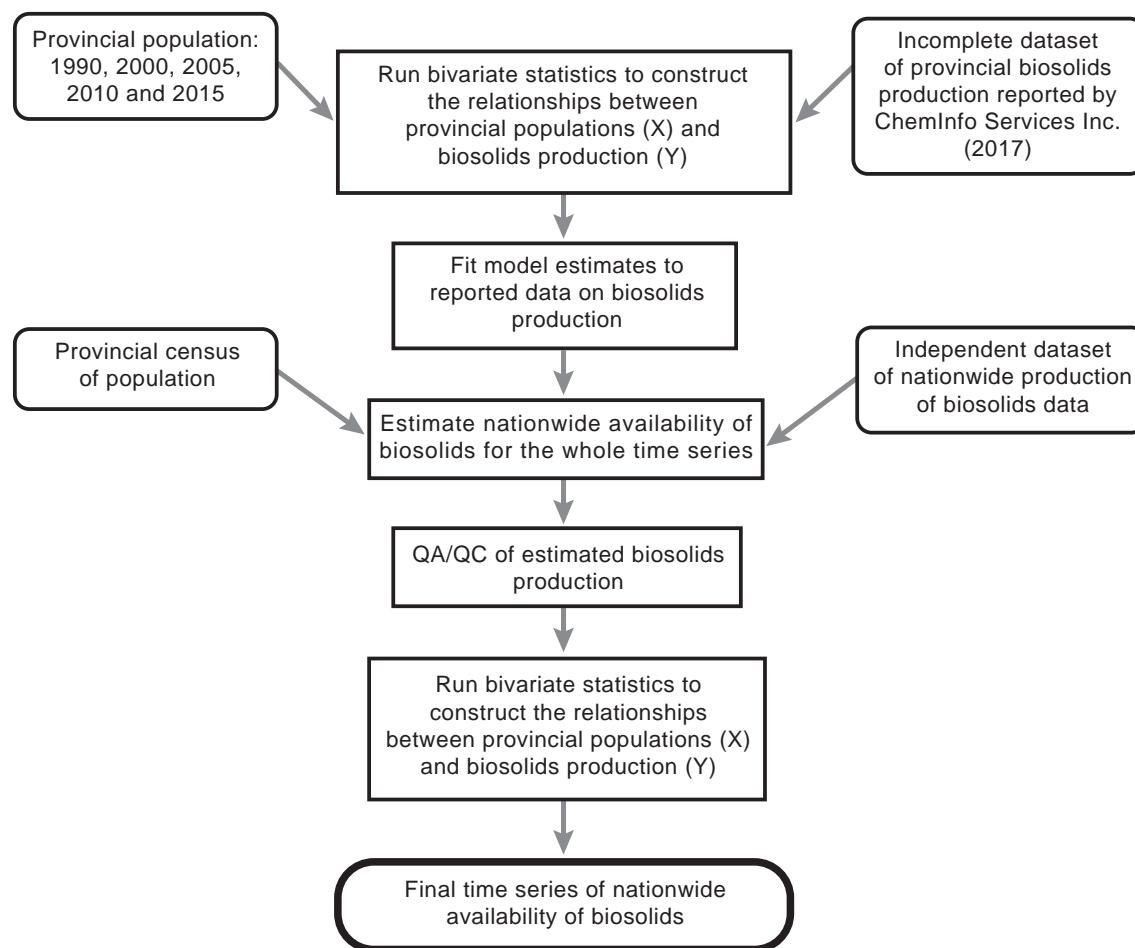


Table A3.4-31 Data Sources Used for Determination of Annual Biosolids Production and Characteristics at the Provincial Scale

Category	Data source	Notes/Comments
Biosolid Production	Cheminfo Services Inc. (2017)	Survey data for biosolid production and fractions that are land-filled, incinerated, land applied, and land-reclamation.
CMA population	https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710013501	Statistics Canada. Population estimates, July 1, by census metropolitan area and census agglomeration, 2016 boundaries.
Provincial population	https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E	Statistics Canada. Census Profile 2016
Federal and provincial regulations	CCME (2010)	CCME. A Review of the Current Canadian Legislative Framework for Wastewater Biosolids.
Biosolids—fractions by digestive processes	Cheminfo Services Inc. (2017)	British Columbia commissioned work.
	Hydromantis Ltd. (2007). GPS-X 5.0 software. General Purpose Simulator – default parameters.	
	Environmental Dynamics Inc. (2017). Beneficial Reuse of Biosolids Jurisdictional Review.	
Nutrient content of biosolids under varied digestion/treatment processes	Dad et al. (2018)	

populations, aggregated CMA populations and provincial populations. Upon regression analysis, the provincial population-based approach was chosen based on the strength of the correlation coefficients. Fortunately, the data generated using this approach were not significantly different from the data reported during the years that Cheminfo Services Inc. (2017) was doing the reporting. Therefore, the smoothed annual provincial biosolids production was derived using the linear approach. For PEI, annual estimates for biosolids production were developed based on expert opinion and using a national average per capita figure ($22.5 \text{ kg person}^{-1} \text{ yr}^{-1}$). This analysis created a complete time series of biosolids production at a provincial scale.

Secondly, the regional rates of land application of biosolids (dry tonnes) were derived using the proportions reported in Cheminfo Services Inc. (2017) adjusted for federal, provincial and municipal regulations, bylaws and restrictions (Table A3.4–31). At the federal level, the regulations imposed by the CCME were applied. Afterwards, provincial restrictions based on the nutrient content of the biosolids and any restrictions on the frequency of biosolids application to lands were incorporated (Table A3.4–31).

Biosolids are typically subject to various digestion and decomposition methods in WWTPs prior to land application. These methods have significant implications for the nutrient content of the biosolids and therefore influence the emission potential when land-applied. Accordingly, as the final step, a combination of survey results and literature analyses was used to identify the major digestion processes, and estimates from Dad et al. (2018) were used to establish the nutrient content of the biosolids.

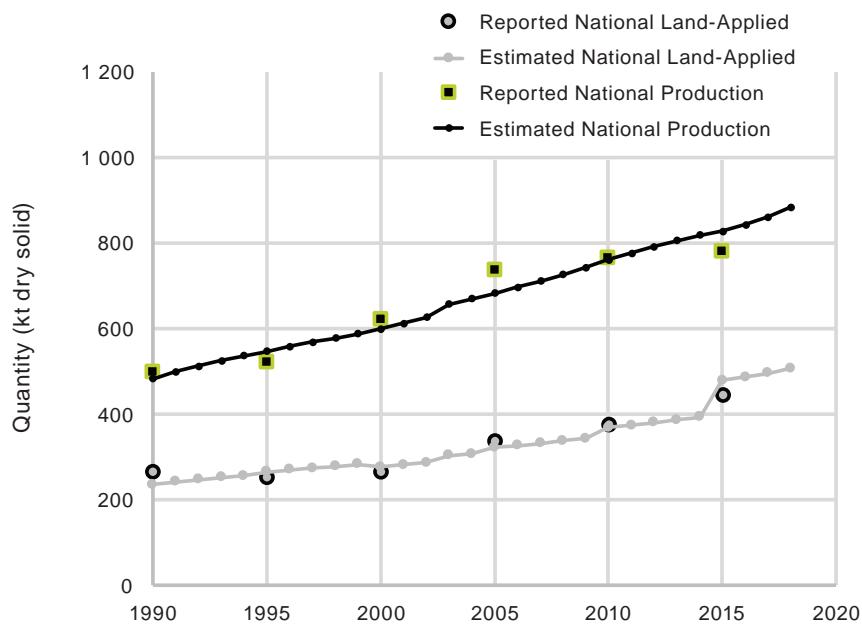
Quality Control and Quality Assurance

For the production data, quality control was conducted at the provincial and national levels. To verify the validity of our data, comparisons were made between the estimated values against independent data points available from literature and from other data sources at the national level. Our data reasonably reflected the production volume of biosolids at the provincial level and represented the changes in provincial regulations that occurred at specific years (Table A3.4–32). At the national level, the data aligned well with the national figures (Figure A3.4–6).

Table A3.4–32 Performance Statistics of Estimated Production Data Against Reported Figures at Provincial CMA and City Scale

Location	Reported Production (kt)	Estimated Production (kt)	% Deviation	Year	Source
Calgary CMA, AB	20.5	23	12.2	Annually	EDI (2017)
City of Edmonton, AB	18	15.6	13.33	1990 to 2004	City of Edmonton (2012)
Halifax CMA, NS	30	13	56.67	Since 2014	EDI (2017)
City of North Battleford, SK	3.5	0.6	82.86	2003–2004	EDI (2017)
City of Toronto, ON	55	64	16.36	Since 2007	AECOM (2009)
City of Kelowna, BC	36.4	3.7	89.84	Since 2006	EDI (2017)

Figure A3.4–6 National Biosolids Production (kt dry solid) Versus the Estimated Total Biosolids Production



Allocation of Biosolids to Ecodistricts and Crops

The amount of biosolids applied as fertilizer at an ecodistrict level was calculated using Equation A3.4–16. Human population was used as a proxy to distribute provincial land-applied biosolids N to the ecodistrict spatial scale. In order to avoid over-application of N in an ecodistrict, a correction procedure was implemented to coordinate the application of manure and biosolids with recommended crop application rates per ecodistrict. First, the total amount of manure N within each ecodistrict was subtracted from the total amount of N required for crop growth, and compared with the amount of biosolids N initially allocated to the ecodistrict. In cases where biosolids N exceeded remaining crop N requirements, the required amount was applied and the excess N was reallocated to other ecodistricts in the province. Next, biosolids N was applied to select crops within each ecodistrict as per provincial and municipal regulations and bylaws limiting the application of biosolids. The amount of biosolids N applied to each crop in a given ecodistrict was then subtracted from the initial crop N requirements, and the modified parameter was used to distribute manure N to crops, following the manure application methodology.

Equation A3.4–16

$$F_{ON=BN,i} = \sum_i \left[Prod_p \times Frac_{LAND,p} \times Frac_{POP,i} \times \sum_r (TN_r \times Frac_{TYPE(r,p)}) \times Frac_{CROP(i,m)} \right]$$

$N_{ON=BN,i}$	=	biosolids nitrogen (BN) applied as organic N fertilizer on cropland in ecodistrict i , kg N yr $^{-1}$
$Prod_p$	=	biosolids production in province p , kg
$Frac_{LAND,p}$	=	fraction of provincial biosolids that are land-applied in province p , unitless
$Frac_{POP,i}$	=	fraction of provincial human population in each ecodistrict i , unitless
TN_r	=	total N content (%) for biosolids type r , percentage
$Frac_{TYPE(r,p)}$	=	fraction of each biosolids treatment type r , in province p , unitless
$Frac_{CROP(i,m)}$	=	fraction of biosolids N applied to crop type m , in ecodistrict i

Inorganic Nitrogen Fertilizers

The method for estimating N₂O emissions from inorganic N fertilizer application on agricultural soils takes into account moisture regimes and topographic conditions. Equation A3.4–17 is used to estimate N₂O emissions by ecodistrict. Emission estimates at the provincial and national scales are obtained by aggregating estimates at the ecodistrict level.

Equation A3.4–17

$$N_2O_{SFN} = \sum [N_{FERT(i,m)} \times (EF_Base_i \times RF_NSE \times RF_NS_{k=IN,m} \times RF_CS_m)] \times 44/28$$

N_2O_{SFN}	=	emissions from inorganic N fertilizer applied to cropland, kg N ₂ O yr ⁻¹
$N_{FERT(i,m)}$	=	inorganic N fertilizer in ecodistrict i , applied to cropping system m as shown in Table A3.4–30, in units of kg N yr ⁻¹
EF_Base_i	=	the weighted average emission factor for ecodistrict i described in Equation A3.4–12, kg N ₂ O-N kg N yr ⁻¹
RF_NSE	=	ratio factor of 1/0.634 for the non-growing season soil N ₂ O emissions, unitless
$RF_NS_{k=IN,m}$	=	ratio factor for source of N, for organic N source $k=ON$ in cropping system m as shown in Table A3.4–30, unitless
RF_CS_m	=	a ratio factor for cropping system (annual or perennial) as shown in Table A3.4–30, unitless
$44/28$	=	coefficient converting N ₂ O-N to N ₂ O

Data for inorganic N fertilizer shipments are available by province only (Statistics Canada, n.d. [h], Statistics Canada, n.d. [i]) and were disaggregated to the ecodistrict level. The approach (Equation A3.4–18) was based on the assumption that the amount of inorganic N fertilizers applied (N_{APPLD}) is equal to the difference between recommended N rates (N_{RCMD}) and organic N available for application on cropland ($N_{ON,CROPS}$).

Equation A3.4–18

$$N_{APPLD,i} = N_{RCMD,i} - N_{ON,CROPS,i}$$

$N_{APPLD,i}$	=	total N fertilizer potentially applied in ecodistrict i , kg N yr ⁻¹
$N_{RCMD,i}$	=	recommended fertilizer application in ecodistrict i , kg N yr ⁻¹
$N_{ON,CROPS,i}$	=	N from organic N applied to crops in ecodistrict i , kg N yr ⁻¹

Based on the work of Yang et al. (2007), N_{RCMD} was estimated as the sum of the products of each crop type and the recommended fertilizer application rate for that crop in an ecodistrict (Equation A3.4–19).

Equation A3.4–19

$$N_{RCMD,i} = \sum_{ij} (CROPA_{ij} \times N_{RECRT,ij})$$

$N_{RCMD,i}$	=	recommended fertilizer application in ecodistrict i , kg N yr ⁻¹
$CROPA_{ij}$	=	area of crop type j in ecodistrict i , ha
$N_{RECRT,ij}$	=	recommended annual N application rate for crop type j in ecodistrict i , kg N ha yr ⁻¹

Because the potential amount of fertilizer needs to be reconciled with the total amount sold in the province (N_{SALES}) to estimate the actual amount applied (N_{FERT}), N_{APPLD} is adjusted in each ecodistrict as follows:

Equation A3.4–20

$$N_{FERT,i} = N_{APPLDi} \times \left[\frac{N_{SALES_p}}{\sum_i^n N_{APPLDi}} \right]$$

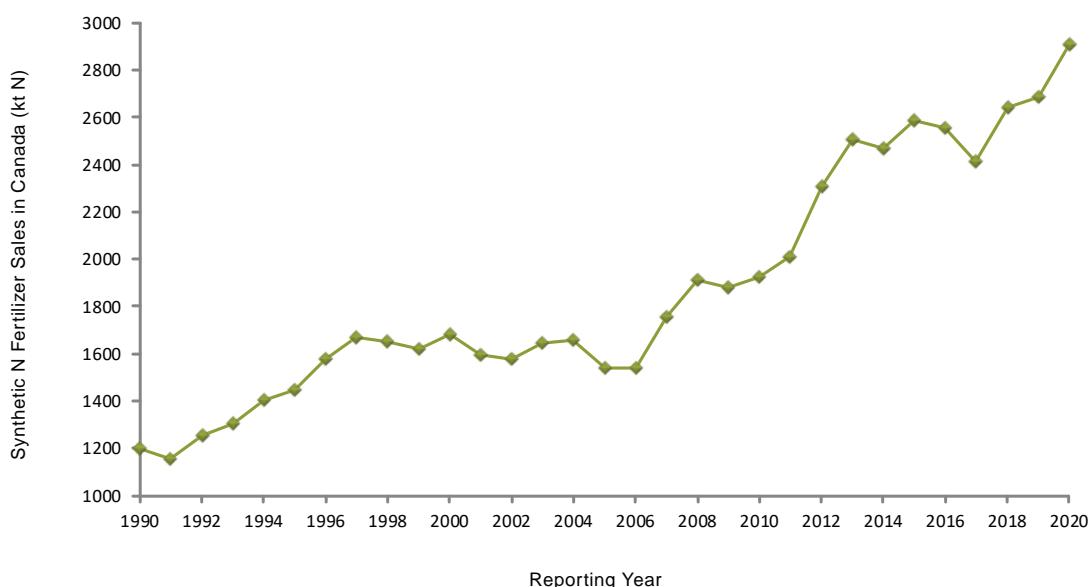
N_{FERTi}	=	total fertilizer N actually applied to all crops in ecodistrict i , kg
N_{SALES_p}	=	total amount of fertilizer N sold in province p , kg
$\sum_i^n N_{APPLDi}$	=	total fertilizer N potentially applied to all crops in all ecodistricts in a province, kg

For years between census years (census years were 1991, 1996, 2001, 2006, 2011 and 2016), N_{RCMD} was linearly interpolated to successively estimate annual values of N_{APPLD} and N_{FERT} at the ecodistrict level. The consumption of inorganic N fertilizers in Canada has significantly increased since 1990, from 1.2 Mt N to 2.9 Mt N, mainly because of the intensification of cropping systems from 1991 to 1997 and increased conversion from perennial to annual crops due to favourable grain prices since 2007 (Figure A3.4–7).

From 1990 to 2002, AAFC collected annual fertilizer N consumption data at the provincial level and published *Canadian Fertilizer Consumption, Shipments and Trade*. From 2003 to 2006, fertilizer N data were collected and published by the Canadian Fertilizer Institute.²⁵ Since 2007, Statistics Canada has collected and published fertilizer shipment data annually (Statistics Canada, n.d. [h]).

25 Available online at <http://www.statcan.gc.ca/daily-quotidien/150213/dq150213f-eng.htm>.

Figure A3.4–7 Inorganic Nitrogen Fertilizer Sales in Canada from 1990 to 2020



Urine and Dung Deposited on Pasture, Range and Paddock by Grazing Animals

Canada uses a country-specific method for estimating N₂O emissions from urine and dung deposited on PRP by grazing animals. The N₂O emission factors for all livestock types were determined on the basis of a research project carried out between 2009 and 2011 for dairy cows in Eastern Canada and for beef cattle in Western Canada. Results from dairy manure in Eastern Canada are available in Rochette et al. (2014). Results from beef manure in Western Canada are summarized in Table A3.4–31 (Lemke et al., 2012). In comparison with the IPCC default EF for major livestock (2%), emission factors were 3.2 times lower in Eastern Canada and 46.5 times lower in Western Canada. Lower emission factors observed on the Canadian Prairies compared with the more humid climate in Eastern Canada are consistent with the findings of Rochette et al. (2008), who reported that moisture deficit—defined as the ratio of precipitation to potential evapotranspiration during the growing season—is a major contributing factor for N₂O emissions on arable cropland in Canada. For Ontario, Quebec and the Atlantic provinces, N₂O EFs are 0.0078 kg N₂O-N kg N⁻¹ for fine-textured soil, 0.0062 kg N₂O-N kg N⁻¹ for medium-textured soil and 0.0047 kg N₂O-N kg N⁻¹ for coarse-textured soil (Rochette et al., 2014). A weighted N₂O EF based on soil texture is calculated for each ecodistrict based on Equation A3.4–12, assuming 75% of excreted N in urine (Rochette et al., 2014). In Western Canada, the N₂O EF is 0.00043 kg N₂O-N kg N⁻¹ (Table A3.4–33). N₂O emissions are calculated using a fixed emission factor-based approach (Equation A3.4–21).

Equation A3.4–21

$$N_2O_{PRP} = \sum[(N_{T,i} \times N_{EX,T} \times N_{PRP,T} \times EF_{PRP,i})] \times 44/28$$

N_2O_{PRP}	=	emissions from urine and dung deposited on pasture, range and paddock from grazing animals, kg N ₂ O yr ⁻¹
$N_{T,i}$	=	animal population of category or subcategory <i>T</i> in ecodistrict <i>i</i> , heads
$N_{EX,T}$	=	annual N excretion rate for animal category or subcategory <i>T</i> , kg N head ⁻¹ yr ⁻¹ (Table A3.4–23 and Table A3.4–25)
$N_{PRP,T}$	=	fraction of manure N excreted on pasture, range and paddock by animal category or subcategory <i>T</i> (Table A3.4–18)
$EF_{PRP,i}$	=	emission factor for manure N deposited by animals on pasture, range and paddock in ecodistrict <i>i</i>
44/28	=	coefficient converting N ₂ O-N to N ₂ O

Animal population data and data sources are detailed in section A3.4.1.

Crop Residue Decomposition

The transformation (nitrification and denitrification) of the N released during the decomposition of crop residues results in N₂O emissions into the atmosphere. A Tier 2 method with country-specific emission factors similar to that for inorganic and organic N fertilizers is used to estimate N₂O emissions from crop residues, based on Equation A3.4–22, Equation A3.4–23 and Equation A3.4–24. The amount of N contained in the aboveground crop residues subjected to field burning at the provincial level is removed from the emission estimate to avoid double counting (see section A3.4.7).

Table A3.4–33 Emissions of Nitrous Oxide from Beef Urine and Dung on Pasture in Western Canada

Site	Treatment	Flux	Target N Rate	Standard Deviation	Emission Factor
					kg N ₂ O-N kg ⁻¹ N
Swift Current, Saskatchewan	Control	0.07		0.04	
	Dung	0.07	500	0.05	0.000002 ± 0.00003
	Urine	0.79	750	1.56	0.001 ± 0.002
Lacombe, Alberta	Control	0.59		0.33	
	Dung	0.50	500	0.41	0 ± 0.0002
	Urine	0.72	750	0.58	0.0002 ± 0.0003
Overall mean					
		Dung			0 ± 0.0001
		Urine			0.0006 ± 0.0012

Note:

Unpublished data (Lemke et al., 2012); urine and dung applied in spring, summer and fall, and repeated one more time along with three replicates, and N₂O flux measurement frequency varied from three times a week immediately after urine and dung application down to once in four weeks depending on the intensity of the flux and weather conditions.

Equation A3.4–22

$$N_2O_{CRN} = \sum [F_{CR(i,m)} \times (EF_Base_i \times RF_NSE \times RF_NS_{k=ON,m} \times RF_CS_m)] \times 44/28$$

N_2O_{CRN}	=	emissions from crop residue decomposition, kg N ₂ O yr ⁻¹
$F_{CR(i,m)}$	=	total amount of crop residue N that is returned to soils for ecodistrict i , excluding N losses due to residue burning, in cropping system m as shown in Table A3.4–30, in units of kg N yr ⁻¹ (see Equation A3.4–23)
EF_Base_i	=	weighted average emission factor for ecodistrict i described in Equation A3.4–12, kg N ₂ O-N kg N yr ⁻¹
RF_NSE	=	ratio factor of 1/0.634 for the non-growing season soil N ₂ O emissions, unitless
$RF_NS_{k=ON,m}$	=	ratio factor for source of N, for organic N source k=ON in cropping system m as shown in Table A3.4–30, unitless
RF_CS_m	=	a ratio factor for cropping system (annual or perennial) as shown in Table A3.4–30, unitless
$44/28$	=	coefficient converting N ₂ O-N to N ₂ O

Equation A3.4–23

$$F_{CR(i,m)} = \sum_{T,i} [P_{T,i} \times FRAC_{RENEW,T,i} \times (R_{AG,T} \times N_{AG,T} + R_{BG,T} \times N_{BG,T})]$$

$F_{CR(i,m)}$	=	total amount of crop residue N that is returned to soils for ecodistrict i and cropping system m , excluding N losses due to residue burning, kg N yr ⁻¹
$P_{T,i}$	=	total production of the T th crop type that is renewed annually in ecodistrict i , kg DM yr ⁻¹ (see Equation A3.4–24)
$FRAC_{RENEW,T,i}$	=	fraction of total area under crop T that is renewed annually in ecodistrict i
$R_{AG,T}$	=	ratio of above-ground residues to harvested yield for crop T , kg dry matter (DM) kg ⁻¹
$N_{AG,T}$	=	N content of above-ground residues for crop T , kg-N kg-DM ⁻¹
$R_{BG,T}$	=	ratio of below-ground residues to harvested yield for crop T , kg DM kg ⁻¹
$N_{BG,T}$	=	N content of below-ground residues for crop T , kg-N kg-DM ⁻¹

Equation A3.4–24

$$P_{T,i} = \frac{A_{T,i} \times Y_{T,i}}{\sum_{i=1}^n (A_{T,i} \times Y_{T,i})} \times P_{T,p} \times (1 - H_2O_T)$$

$P_{T,i}$	=	total production of the T th crop type that is renewed annually in ecodistrict i , kg DM yr ⁻¹
$A_{T,i}$	=	area under crop type T in ecodistrict i , ha
$Y_{T,i}$	=	average crop yield for crop type T in ecodistrict i , kg ha ⁻¹ yr ⁻¹
$\sum_{i=1}^n (A_{T,i} \times Y_{T,i})$	=	sum of total production for crop type T over all ecodistricts in a province
$P_{T,p}$	=	total crop production for crop type T in province p , kg DM yr ⁻¹
H_2O_T	=	water content of crop T , kg kg ⁻¹

Statistics Canada collects and publishes annual field crop production data by province (Statistics Canada, n.d. [g]). Crops include wheat, barley, corn/maize, oats, rye, mixed grains, flax seed, canola, buckwheat, mustard seed, sunflower seed, canary seeds, fodder corn, sugar beets, tame hay, dry peas, soybean, dry white beans, coloured beans, chickpeas and lentils. The area seeded and the yield of each crop are reported at the census agricultural region and provincial levels, and yields have been allocated to SLC polygons through area overlays by AAFC. Specific parameters for each crop type are listed in Janzen et al. (2003). Statistics Canada survey data are based on the COA, and therefore general revisions to the survey time series may occur when COA data are modified due to refinements of the calibration model or other changes. Survey data are also occasionally revised by Statistics Canada due to error correction, and alignment with other supply and disposition statistics such as exports.

Mineralization Associated with Loss of Soil Organic Matter

The amount of N in mineral soils that is mineralized in association with loss of soil organic matter as a result of changes to land management practices can result in additional N₂O emissions from the Cropland Remaining Cropland category. A database containing soil organic carbon (SOC) and N for all major soils in Saskatchewan (a data set of about 600) was used to derive an average C:N ratio of 11 with a standard deviation of 1.9. The C:N ratio of agricultural soils is considered to be consistent among regions. The 2006 IPCC Guidelines propose a range of C:N ratios from 8 to 15. A Tier 2 method with country-specific emission factors is used for emission estimates (see Equation A3.4–25 and Equation A3.4–26).

Equation A3.4–25

$$F_{SOM,i} = \sum_{LM} [(\Delta C_{Mineral,LM} \times \frac{1}{R}) \times 1000]$$

$F_{SOM,i}$	=	the net annual amount of N mineralised in mineral soils in ecodistrict i as a result of loss of SOC through change in land management practices, crop productivity and manure application, kg N
$\Delta C_{Mineral,LM}$	=	average annual loss of SOC for each land management practice (LM), Mg C
R	=	C:N ratio of the soil organic matter (11.0 ± 1.9)

Equation A3.4–26

$$N_2O_{FSOM} = \sum_i (F_{SOM,i} \times EF_{Base,i} \times RF_{NSE} \times RF_{NS_{k=ON,m=A}} \times RF_{CS_{m=A}}) \times \frac{44}{28}$$

N_2O_{FSOM}	=	emissions associated with loss of soil organic matter due to changes in land management practices, crop productivity and manure application, kg N ₂ O yr ⁻¹
$F_{SOM,i}$	=	the net annual amount of N mineralised in mineral soils as a result of loss of SOC through change in land management practices, crop productivity and manure application, for ecodistrict i , kg N
$EF_{Base,i}$	=	weighted average emission factor for ecodistrict i described in Equation A3.4–12, kg N ₂ O-N kg N yr ⁻¹
RF_{NSE}	=	ratio factor of 1/0.634 for the non-growing season soil N ₂ O emissions, unitless
$RF_{NS_{k=ON,m=A}}$	=	ratio factor for source of N, for organic N source $k=ON$ in for annual cropping system, as shown in Table A3.4–30, unitless
$RF_{CS_{m=A}}$	=	a ratio factor for annual cropping system as shown in Table A3.4–30, unitless
$44/28$	=	coefficient converting N ₂ O-N to N ₂ O

Activity data on SOC loss at an ecodistrict level over the time series that is reported in the LULUCF Cropland Remaining Cropland category are used for soil N₂O estimates associated with the loss of soil organic matter.

Cultivation of Organic Soils (Histosols)

Cultivation of organic soil (histosols) for annual crop production produces N₂O. The IPCC Tier 1 methodology is used to estimate N₂O emissions from cultivated organic soils (Equation A3.4–27).

Equation A3.4–27

$$N_2O_H = \sum_i (A_{os,i} \times EF_{HIST}) \times \frac{44}{28}$$

N_2O_H	=	emissions from cultivated histosols, kg N ₂ O yr ⁻¹
$A_{os,i}$	=	area of cultivated organic soils in province i , ha
EF_{HIST}	=	IPCC default emission factor for mid-latitude organic soils, 8.0 kg N ₂ O-N ha ⁻¹ yr ⁻¹ (IPCC, 2006)
$44/28$	=	coefficient converting N ₂ O-N to N ₂ O

Table A3.4-34 Soil N₂O Ratio Factors for Tillage by Ecozone

Ecozone	RF_TILL
Taiga Plains	0.73 ^a
Boreal Shield	1 ^b
Atlantic Maritime	1 ^b
Mixedwood Plains	1 ^b
Boreal Plains	0.73 ^a
Prairies	0.73 ^a
Pacific Maritime	1 ^b
Montane Cordillera	0.73 ^a
Notes:	
a. Source = Liang et al. (2020)	
b. Modified from Liang et al. (2020) based on expert consultation with Canadian scientific community	

Areas of cultivated histosols at a provincial level are not collected as part of the COA. Consultations with numerous soil and crop specialists across Canada indicate that the total area of cultivated organic soils in Canada was 16 kilohectares (Liang et al., 2004) and remains constant over time.

Change in N₂O Emissions from Adoption of No-Till and Reduced Tillage

This category is specific to Canada and does not derive from additional N inputs such as fertilizer, manure and crop residue, but rather is implemented as modifications to EF_Base due to the switch from conventional to conservation tillage practices—namely no-till (NT) and reduced tillage (RT).

To quantify the impact of tillage practices on N₂O emissions, a tillage ratio factor (RF_Till), defined as the ratio of mean N₂O fluxes of NT or RT to mean N₂O fluxes of IT (N₂O_{NT}/N₂O_{IT}), is used (Table A3.4-34). The fraction of cropland under NT and RT (FRAC_{NT-RT}) for each ecodistrict is derived from the COA and is identical to that used in the LULUCF Cropland Remaining Cropland category for NT and RT practices (see section 4—Cropland in Annex 3.5). These data are published at the census agricultural region, census division, and provincial and national levels. Annual FRAC_{NT-RT} between two consecutive census years is interpolated.

Equation A3.4-28

$$N_2O_{TILL} = \sum_i \left[(N_2O_{k=IN,m=A,i} + N_2O_{k=ON,m=A,i} + N_2O_{k=CN,m=A,i}) \times (FRAC_{NT-RT,i} \times (RF_Till_z - 1)) \right]$$

N ₂ O _{TILL}	=	change in N ₂ O emissions resulting from the adoption of NT and RT, kg N ₂ O yr ⁻¹
N ₂ O _{k=IN,m=A,i}	=	soil N ₂ O emissions from inorganic fertilizer N use on annual crop in ecodistrict i, kg N ₂ O yr ⁻¹
N ₂ O _{k=ON,m=A,i}	=	soil N ₂ O emissions from manure N use on annual crop in ecodistrict i, kg N ₂ O yr ⁻¹
N ₂ O _{k=CN,m=A,i}	=	soil N ₂ O emissions from crop residue N on annual crop in ecodistrict i, kg N ₂ O yr ⁻¹
FRAC _{NT-RT,i}	=	fraction of cropland on NT and RT in ecodistrict i
RF _{TILLz}	=	ratio factor adjusting EF_Base due to the adoption of NT and RT, for ecozone z

The fraction of cropland under NT and RT (FRAC_{NT-RT}) for each ecodistrict was derived from the COA and is identical to that used in the LULUCF Cropland Remaining Cropland category for NT and RT practices (see section 4—Cropland in Annex 3.5). These data are published at the census agricultural region, census division, and provincial and national levels. Annual FRAC_{NT-RT} between two consecutive census years is interpolated.

N₂O Emissions Resulting from Irrigation

Higher soil water content under irrigation increases N₂O emissions by increasing biological activity and reducing soil aeration (Jambert et al., 1997). Accordingly, highest N₂O emissions from agricultural soils in the northwestern United States (Liebig et al., 2005) and Western Canada (Hao et al., 2001a) were observed on irrigated cropland, followed by non-irrigated cropland and rangeland. Field studies directly comparing N₂O emissions under irrigated and non-irrigated conditions are lacking in Canada. Therefore, an approach was used based on the assumptions that: (1)

irrigation water stimulates N₂O production in a way similar to rainfall; (2) irrigation is applied to eliminate any moisture deficit such that “precipitation + irrigation water = potential evapotranspiration”; and (3) the effect of irrigation on N₂O emissions is in addition to effects of the non-irrigated area within an ecodistrict. Consequently, the effect of irrigation on N₂O emissions from agricultural soils was accounted for using an EF_Base estimated at a P=PE for the irrigated areas of an ecodistrict:

Equation A3.4–29

$$N_2O_{IRRI} = \sum_i \left[\sum_k (N_2O_{k,i}) \times (FRAC_{IRRI,i} \times (RF_{IRRI,i} - 1)) \right]$$

N_2O_{IRRI}	=	emissions from irrigation, kg N ₂ O yr ⁻¹
$N_2O_{k,i}$	=	soil N ₂ O emissions from N source k for annual crops in ecodistrict i, kg N ₂ O yr ⁻¹
$RF_{IRRI,i}$	=	ratio factor for irrigation in ecodistrict i, unitless (see Equation A3.4–30)
$FRAC_{IRRI,i}$	=	fraction of irrigated cropland in ecodistrict i

Equation A3.4–30

$$RF_{IRRI,i} = \frac{EF_{CT_{P=PE,i}}}{EF_{CT_{i,P}}}$$

$RF_{IRRI,i}$	=	emissions from irrigation, kg N ₂ O yr ⁻¹
$EF_{CT_{i,P}}$	=	Soil N ₂ O emission factor calculated at P for ecodistrict i, kg N ₂ O-N kg ⁻¹ N (see Figure A3.4–4)
$EF_{CT_{i,P=PE}}$	=	Soil N ₂ O emission factor calculated at P=PE for ecodistrict i, kg N ₂ O-N kg ⁻¹ N

The fraction FRAC_{IRRI} is derived from the COA for each ecodistrict (see section 4—Cropland in Annex 3.5). Annual FRAC_{IRRI} between two consecutive census years is adjusted through interpolation.

A3.4.5.2. Indirect N₂O Emissions from Agricultural Soils

Volatilization and Redeposition of Nitrogen

The IPCC Tier 1 methodology is used to estimate indirect N₂O emissions from volatilization and redeposition of inorganic and organic N. The emission calculation is shown in Equation A3.4–31.

Equation A3.4–31

$$N_2O_{VD} = \sum_i [(N_{FERT,TN,i} \times FRAC_{GASFNT,i}) + (MN_{PRP,iT} \times FRAC_{GasMS-PRP,T}) + (F_{ON,i} \times FRAC_{GASM,i})] \times EF_4 \times \frac{44}{28}$$

N_2O_{VD}	=	emissions from volatilization and redeposition of N, kg N ₂ O yr ⁻¹
$N_{FERT,TN,i}$	=	inorganic N consumption for each type of N fertilizers including urea, urea ammonium nitrate, anhydrous ammonia and others in ecodistrict i, kg N yr ⁻¹
$FRAC_{GASFNT,i}$	=	fraction of inorganic N fertilizers applied to soils that volatilizes as NH ₃ -N, kg NH ₃ -N kg N ⁻¹ , determined by a country-specific method in an ecodistrict i (see Equation A3.4–17)
$MN_{PRP,iT}$	=	amount of urine and dung N excreted on pasture, range and paddock by animal category or subcategory T in an ecodistrict i, kg N yr ⁻¹
$FRAC_{GasMS-PRP,T}$	=	fraction of volatilized manure N deposited on pasture, range and paddock by animal category or subcategory T: 0.2 kg (NH ₃ -N + NO _x -N) kg N ⁻¹ (IPCC, 2006) for all livestock categories except Dairy Cattle (Table A3.4–40)
$N_{MN-CROPS,i}$	=	organic N fertilizers applied on cropland in ecodistrict i, kg N yr ⁻¹ (see Table A3.4–38)
$FRAC_{GASM,i}$	=	fraction of volatilized organic N fertilizers in ecodistrict i: 0.21 kg (NH ₃ -N + NO _x -N) kg N ⁻¹ for all livestock (IPCC, 2019) except the Dairy Cattle and Swine categories (Table A3.4–38).
EF_4	=	emission factor from atmospheric deposition of N (see Table A3.4–26)
$44/28$	=	coefficient converting N ₂ O-N to N ₂ O

Table A3.4–35 **Coefficients for Crop Type, Inorganic N Fertilizers, Method of Fertilizer Application, Soil Chemical Properties and Climate Developed by Bouwman et al. (2002b)**

Conditions where coefficient used		Coefficients
Crop Type	Annual crops	-0.045
	Perennial crops	-0.158
Fertilizer Type	Urea	0.666
	Urea ammonium nitrate	0.282
	Anhydrous ammonia	-1.151
	Other N sources	-0.238
Method of Application	Broadcast onto surface	-1.305
	Incorporated	-1.895
Soil Chemical Properties	Soil pH < 7.25	-1
	Soil pH 7.25 ~ 8.5	-0.608
	Soil CEC < 250 mmol kg ⁻¹	0.0507
	Soil CEC > 250 mmol kg ⁻¹	0.0848
Climate	Temperate	-0.402

A country-specific method was used to estimate ammonia emissions from inorganic N application. The method for deriving ammonia emission factors closely follows the approach of Sheppard et al. (2010a), who applied the regression model developed by Bouwman et al. (2002b) to derive regionally specific emission factors for different ecoregions in Canada. This approach derives ammonia emission factors based on the type of inorganic N fertilizers, degree of incorporation into soil, crop type and soil chemical properties (Equation A3.4–32).

Equation A3.4–32

$$FRAC_{GASF\ TN, i} = 100 \times EXP(sum\ of\ relevant\ coefficients)$$

$FRAC_{GASF\ TN, i}$	=	ammonia emission factor for each type of inorganic N fertilizer in ecodistrict <i>i</i> , %
sum of relevant coefficients	=	coefficients for crop type, type of inorganic N fertilizers, method of N application, soil chemical properties and climate, unitless (see Table A3.4–35)
100	=	conversion of fraction to percent
EXP	=	exponential

The method of application for each type of inorganic N fertilizers for Eastern and Western Canada is provided in Sheppard et al. (2010a). Soil properties, pH and cation exchange capacity (CEC) are derived from CANSIS soil polygon information and are based on fractional distributions of soil series having pH < 7.25 and CEC < 250 me kg⁻¹, pH < 7.25 and CEC > 250 me kg⁻¹, pH > 7.25 and CEC < 250 me kg⁻¹, and pH > 7.25 and CEC > 250 me kg⁻¹. Statistics Canada collects and publishes annual inorganic N fertilizer shipment data including urea, urea ammonium nitrate, anhydrous ammonia and others (Statistics Canada, n.d. [h], Statistics Canada, n.d. [i]). The application of this equation results in spatially specific emission factors for inorganic N fertilizers applied to annual crops. Provincial averages by fertilizer type (Table A3.4–36) are calculated based on the spatial distribution of soil chemical properties and climate for each individual ecodistrict in each province and, as a consequence, the fraction ($FRAC_{GASF}$) of ammonia volatilized by province varies slightly from year to year based on fertilizer sales (Table A3.4–37). More detail on methods of estimating ammonia emission factors from inorganic N fertilizers can be found in Sheppard et al. (2010a), and simplifications used to convert monthly emissions calculated in the original publication to an annual estimate are documented in Liang (2014). Briefly, based on the data provided in Sheppard et al. (2010a), it is assumed that inorganic N fertilizers are applied in either spring or fall when temperatures are similar. Therefore, a single temperature representing annual applications per ecoregion is used to estimate emissions. According to this approach, the fraction of fertilizers emitted during fertilizer application ranges from roughly 5% to a maximum of 10% (Table A3.4–37), depending on the year and province.

Table A3.4–36 Ammonia Emission Factors of Inorganic Nitrogen Fertilizers Applied to Annual Crops Weighted Based on Soil Properties for Each Province (%)

Province	Annual			
	Urea	Anhydrous NH ₃	UAN	Other
AB	5	4.2	3.8	5.4
BC	4.8	4	3.7	5.2
MB	5.8	4.9	4.5	6.3
NB	7.4	3.9	4.5	4.5
NL	7.4	3.9	4.5	4.5
NS	7.3	3.9	4.4	4.4
ON	8.2	4.4	5	4.9
PE	7.3	3.9	4.4	4.4
QC	7.4	4	4.5	4.5
SK	5.1	4.2	3.9	5.5

Table A3.4–37 Fractions of N Volatilized (FRAC_{GASF}) as Ammonia Resulting from the Application of Inorganic N Fertilizer, from Select Years, 1990–2020, at a Provincial Scale

Implied EF (kg NH ₃ -N volatilized / kg inorganic fertilizer N applied)										
Year	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
1990	0.06	0.09	0.06	0.07	0.08	0.08	0.08	0.06	0.09	0.05
1995	0.06	0.09	0.07	0.07	0.08	0.08	0.08	0.06	0.08	0.06
2000	0.06	0.10	0.07	0.06	0.07	0.07	0.08	0.05	0.08	0.06
2005	0.06	0.10	0.07	0.06	0.07	0.07	0.08	0.06	0.07	0.06
2010	0.06	0.09	0.07	0.05	0.07	0.06	0.08	0.05	0.07	0.06
2015	0.06	0.09	0.07	0.06	0.07	0.07	0.07	0.05	0.07	0.06
2016	0.06	0.09	0.07	0.05	0.07	0.06	0.08	0.05	0.07	0.06
2017	0.06	0.09	0.07	0.05	0.07	0.06	0.07	0.05	0.07	0.06
2018	0.06	0.09	0.07	0.05	0.07	0.06	0.08	0.05	0.08	0.06
2019	0.06	0.09	0.07	0.06	0.07	0.06	0.07	0.05	0.08	0.06
2020	0.06	0.09	0.07	0.06	0.08	0.07	0.07	0.06	0.07	0.06

Table A3.4–38 Fractions of Dairy Cattle N Volatilized as Ammonia Resulting from the Application of Manure N Fertilizer, from Select Years, 1990–2020, at a Provincial Scale

Implied EF (kg NH ₃ -N volatilized / kg manure N applied)										
Year	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
1990	0.13	0.10	0.16	0.20	0.19	0.20	0.18	0.18	0.17	0.15
1995	0.13	0.09	0.16	0.19	0.19	0.19	0.18	0.18	0.17	0.15
2000	0.12	0.09	0.15	0.18	0.19	0.18	0.17	0.18	0.16	0.14
2005	0.11	0.08	0.14	0.17	0.19	0.16	0.17	0.18	0.15	0.13
2010	0.11	0.09	0.13	0.16	0.19	0.15	0.16	0.17	0.15	0.12
2015	0.11	0.09	0.13	0.16	0.19	0.15	0.16	0.17	0.15	0.12
2016	0.11	0.09	0.13	0.16	0.19	0.15	0.16	0.17	0.15	0.12
2017	0.11	0.09	0.13	0.16	0.19	0.15	0.16	0.17	0.15	0.12
2018	0.11	0.09	0.13	0.16	0.19	0.15	0.16	0.17	0.15	0.12
2019	0.11	0.09	0.13	0.16	0.19	0.15	0.16	0.17	0.15	0.12
2020	0.11	0.09	0.13	0.16	0.19	0.15	0.16	0.17	0.15	0.12

Table A3.4–39 Fractions of Swine N Volatilized as Ammonia Resulting from the Application of Manure N Fertilizer, from Select Years, 1990–2020, at a Provincial Scale

Year	Implied EF (kg NH ₃ -N volatilized / kg manure N applied)									
	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
1990	0.14	0.22	0.14	0.28	0.22	0.28	0.21	0.28	0.26	0.15
1995	0.13	0.22	0.12	0.27	0.22	0.27	0.21	0.27	0.25	0.13
2000	0.13	0.22	0.11	0.25	0.23	0.25	0.20	0.26	0.25	0.12
2005	0.12	0.22	0.11	0.25	0.22	0.24	0.20	0.25	0.24	0.12
2010	0.12	0.21	0.11	0.24	0.23	0.23	0.20	0.25	0.24	0.12
2015	0.13	0.21	0.11	0.24	0.22	0.25	0.20	0.25	0.24	0.12
2016	0.13	0.21	0.11	0.24	0.22	0.25	0.20	0.25	0.24	0.12
2017	0.13	0.21	0.11	0.24	0.22	0.25	0.20	0.25	0.24	0.12
2018	0.13	0.21	0.11	0.24	0.22	0.25	0.20	0.25	0.24	0.12
2019	0.13	0.21	0.11	0.24	0.22	0.25	0.20	0.25	0.24	0.12
2020	0.13	0.20	0.11	0.24	0.23	0.26	0.20	0.25	0.24	0.12

Table A3.4–40 Fractions of Dairy Cattle N Volatilized as Ammonia Resulting from Deposition on Pasture, Range and Paddock, in 2020, at a Provincial Scale

Province	Implied EF (kg NH ₃ -N volatilized / kg manure N)
AB	0.035
BC	0.044
MB	0.036
NB	0.039
NL	0.036
NS	0.039
ON	0.042
PE	0.039
QC	0.036
SK	0.036

Leaching and Runoff

A modified IPCC Tier 1 methodology is used to estimate N₂O emissions from leaching and runoff of inorganic and organic N fertilizers, and crop residue N from agricultural soils:

Equation A3.4–33

$$N_2O_L = \sum_i [(N_{FERT,i} + N_{MAN-CROPS,i} + MAN_{PRP,i} + N_{RES,i}) \times FRAC_{LEACH,i} \times EF_5] \times \frac{44}{28}$$

- N_2O_L = emissions from leaching and runoff of N, kg N₂O yr⁻¹
 $N_{FERT,i}$ = inorganic N fertilizers applied for ecodistrict i , kg N
 $N_{MAN-CROPS,i}$ = organic N fertilizers applied for ecodistrict i , kg N
 $MAN_{PRP,i}$ = urine and dung deposited on pasture, range and paddock for ecodistrict i , kg N
 $N_{RES,i}$ = crop residue N for ecodistrict i , kg N
 $FRAC_{LEACH,i}$ = fraction of N that is lost through leaching and runoff for ecodistrict i , as defined below
 EF_5 = leaching/runoff emission factor: 0.0075 kg N₂O-N kg N⁻¹ (IPCC, 2006)
 $44/28$ = coefficient converting N₂O-N to N₂O

Determining the Fraction of Nitrogen that is Leached (FRAC_{LEACH}) at the Ecodistrict Level in Canada

In Canada, leaching losses of N vary widely among regions. In some farming systems of southern British Columbia, high N inputs in humid conditions may lead to losses greater than 100 kg N ha⁻¹ year⁻¹ (Paul and Zebarth, 1997; Zebarth et al., 1998). Those farming systems, however, represent only a small fraction of Canadian agroecosystems. In Ontario, Goss and Goorahoo (1995) predicted leaching losses of 0 to 37 kg N ha⁻¹, representing between 0% and 20% of N inputs. Leaching losses in most of the Prairies region may be smaller due to lower precipitation and lower N inputs on a per area basis. Based on a long-term experiment in central Alberta, Nyborg et al., (1995) suggested that leaching losses were minimal, and Chang and Janzen (1996) found no evidence of N leaching in non-irrigated, heavily manured plots, despite large accumulations of soil nitrate in the soil profile.

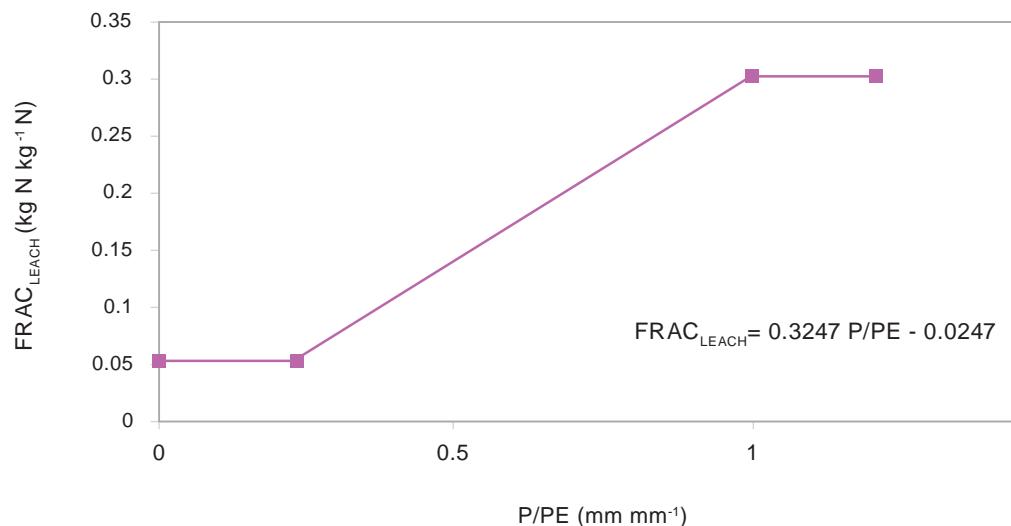
The values for FRAC_{LEACH} can be as low as 0.05 in regions where rainfall is much lower than potential evapotranspiration, such as in the Prairies region of Canada, or as high as 0.3 in humid regions (IPCC, 2006) of Eastern Canada. Accordingly, it was assumed that FRAC_{LEACH} would vary from 0.05 to 0.3, depending on the ecodistrict.

For ecodistricts with a P/PE value for the growing season (May through October) greater than or equal to 1, the maximum FRAC_{LEACH} value of 0.3 (IPCC, 2006) was assigned. For ecodistricts with the lowest P/PE value (0.23), a minimum FRAC_{LEACH} value of 0.05 was assigned. For ecodistricts with a P/PE value that ranged from 0.23 to 1, FRAC_{LEACH} was estimated by the linear function that joins the two-end points (P/PE, FRAC_{LEACH}) = (1,0.3; 0.23,0.05) (Figure A3.4–8).

Data sources for N_{FERT}, N_{MAN-CROPS}, MAN_{PRP} and N_{RES} (section A3.4.5.1) at an ecodistrict level are provided in the previous sections.

Long-term normals of monthly precipitation and potential evapotranspiration from May to October, 1971–2000 (AAFC-archived database) were used to calculate FRAC_{LEACH} at an ecodistrict level.

Figure A3.4–8 Determination of the Ecodistrict FRAC_{LEACH} Values



A3.4.6. Uncertainty Estimates of N₂O Emissions

A
3

A comprehensive uncertainty analysis was completed for all methodologies used in the calculation of N₂O from livestock and agricultural soils for 2010 (Karimi-Zindashty et al., 2014). The analysis has not yet been published, and limited depth of analysis could be carried out due to the size and complexity of the Canadian N₂O quantification approach and the upper limits of the data processing capability of the Analytica software. However, the analysis did provide the uncertain bounds around the principal emission source categories. For this submission, the uncertainty ranges (percentages) developed for 2010 means were applied to means for the current year. In the analysis, a stochastic reproduction of the complete N₂O emission methodology was built in Analytica® at the ecodistrict scale, and a MCS was run according to the methodology proposed in the Good Practice Guidance (IPCC, 2000). A sensitivity analysis was carried out to identify the parameters that contributed most to different emission source categories.

The parameters used in the calculation of N₂O emissions can be divided into three categories: (1) those associated with information at the ecodistrict scale, (2) provincial-scale data and (3) IPCC/national-scale parameters (Table A3.4–39). The majority of national-scale parameters are taken directly from the 2006 IPCC Guidelines (IPCC, 2006) or from the original country-specific methodological development work carried out by Rochette et al. (2008), derived either analytically or through expert opinion based on a panel of four experts in agricultural GHG emissions. Provincial-scale parameters include fertilizer sales and characteristics of crop production, the source of uncertainty being the Statistics Canada survey uncertainty and expert opinion on characteristics of crop production. The uncertainty of livestock populations and management parameters for animal categories were identical to that discussed in sections A3.4.2.4 and A3.4.3.9; the distributions used to define uncertainties can be found in Table A3.4–12 and Table A3.4–22. Landscape-scale parameters were derived from the agricultural soil landscape parameter database developed by AAFC and used in the production of cropland estimates for LULUCF. Specific landscape-parameter uncertainty was based on the general rules used in the production of uncertainty estimates for cropland C, which postulates that the uncertainty of a parameter at the landscape scale is inversely proportional to the relative size of the landscape unit, i.e., smaller parameters associated with smaller ecodistricts have greater uncertainty. The bounds of the uncertainty for different parameters varied. For example, uncertainties around animal distribution was ±30% for small ecodistricts and ±5% for large ecodistricts, whereas for the fraction of lowland soil in a given ecodistrict, variability was bounded as ±10% for small ecodistricts and ±1.25% for large ecodistricts. The current analysis does not include new country-specific emission factors for N₂O emissions from animal manure deposited on pasture, range and paddock, but does include the analysis of emissions considering the 2006 IPCC Guidelines leaching emission factor.

The summary results of the uncertainty analysis on emissions of N₂O are reported in Chapter 5. The relative uncertainty range for N₂O emissions from agricultural sources is 56% (-27% to +29% of the mean). Most uncertainty is associated with indirect emissions and specifically with the indirect emission factors for volatilized and leached N, with the estimate of indirect emissions uncertainty of 126% (-58% to +68% of the mean). The emissions are skewed to the lower end of the emission probability distribution, because emission factor uncertainty is bounded by zero and emission factor variability is expressed as a factor on the lower scale; a change from 1% to 0.2% has a smaller impact on total emissions than a change from 1% to 5% at the upper end of the probability distribution. The uncertainty range of direct N₂O emissions from agricultural soils is 69% (-31% to +38% of the mean). There have been few complete studies of uncertainty from emissions of N₂O in the literature. In a study directly comparable to this particular uncertainty analysis, Monni et al. (2007) estimated that total N₂O emissions in Finland ranged from -50% to +70% of the mean emission estimate. Their methodology included a mixture of country-specific and default Tier 1 methodology to produce emission estimates. In a recent study of uncertainty in the United Kingdom, Milne et al. (2013) observed high uncertainty ranges for direct, indirect and total N₂O emissions, specifically -56% to +140%, -91% to +370%, and -55% to +110%, respectively. Our parameter uncertainty was similar to that used by the UK researchers, but it is suspected that the high degree of spatial disaggregation in the Canadian N₂O quantification approach resulted in slightly lower overall uncertainty. The uncertainty associated with the fraction of emission(s) from inorganic N fertilizers would be reduced from ±200% by the IPCC default (IPCC, 2006) given the country-specific approach applied in this submission.

Sensitivity analysis indicated that indirect EF uncertainties were the largest contributors to overall uncertainty. Uncertainty of direct soil emissions was dominated by the use of uncertainty in the Tier 1 emission factor for emissions from pasture, range and paddock (PRP), the slope of P/PE regression equation and the emission factor modifier for tillage and texture (RF_TILL, RF_TX). The EF for solid manure systems was the largest source of uncertainty in the estimate of N₂O emissions from AWMS. Reduction of uncertainty will require the replacement of Tier 1 default emission factors and modifiers in the methodology.

Table A3.4-41 Uncertainty Parameters Used in the Calculation of Agricultural N₂O Emissions

Parameter	Coefficient/Parameter Source	Distribution Type	Uncertainty Range	Most Likely Value ^b	Uncertainty Distribution Source and Notes
IPCC and National Scale Parameters					
Animal populations and characterization data ^a					Karimi-Zindashty et al. (2012) from Statistics Canada, personal communication
N excretion	2006 IPCC Guidelines	Normal	±50%	IPCC default	
FRAC _{GAS} /FRAC _{LOSSMS}		Triangular	IPCC default	IPCC default	See Table 10.22/10.23 of 2006 IPCC Guidelines
AWMS emission factor		Triangular	Liquid 0.0005–0.002 PRP -0.007–0.06	Minimum liquid 0.001 Maximum PRP -0.02	2006 IPCC Guidelines variable depending on the manure storage type
Crop characteristics					
H ₂ O content	Janzen et al. (2003)	Normal	±15%		Expert consultation
Relative DM allocation of residue (product, aboveground and belowground)					
FRAC _{Renew} (duration)					
N concentration in residue (aboveground and belowground)					
Direct and indirect emission factors/modifiers					
P/PE regression parameters	Rochette et al., 2008	Normal	Intercept ±54% Slope ±21%		Expert consultations
FRAC _{LEACH} calculation parameters			Intercept ±54% Slope ±21%		
RF_TILL			±100%		
RF_TX			±30%		
EF _{LEACH}	2006 IPCC Guidelines	Triangular	0.002–0.12	0.025	2006 IPCC Guidelines
EF _{VD}			0.002–0.05	0.01	
EF _{HIST}			2–24	8	
Provincial – Scale Parameters					
Fertilizer application rate (kg/ha)	Factors are drawn from common usage in AAFC ^c literature and modelling studies	Normal	±15%		Expert consultation
Provincial fertilizer sales	Statistics Canada	Normal	±15%		Interpretation of data quality evaluation in Statistic Canada Report
Ecodistrict – Scale Parameters					
P and PE	Weather Station Data	Normal	5–15%		Based on individual weather station data, 30-year average
Total ecodistrict area	AAFC ^c geographically referenced soil landscape agricultural database, derived from <i>Census of Agriculture</i> , 1990–2011	Normal	Function of Relative Ecodistrict Size: maximum uncertainty of 30% for small ecodistricts, decreases to minimum of 3% for largest ecodistricts, maximums and minimums vary depending on the parameter		Based on the uncertainty methodology used in the carbon quantification methodology for croplands
Crop areas					
Animal population distribution to ecodistrict					
RF_Topo (proportion of lowland soils in ecodistrict)					
Extent of organic soils					
Irrigated soil area					
Annual soil texture					
Perennial soil texture					

Note:

- a. Uncertainty associated with most livestock parameters can be found in section A3.4.2.4 and section A3.4.3.8, and the distributions used to define uncertainties can be found in Table A3.1–7 and Table A3.2–8.
- b. Reported where applicable when using a triangular distribution.
- c. Agriculture and Agri-Food Canada.

A3.4.7. CH₄ and N₂O Emissions from Field Burning of Agricultural Residues

Crop residues are sometimes burned in Canada, for convenience and as a means of disease control through residue removals, although expert opinion suggests that this practice has declined in recent years because of soil quality and environmental issues.

Field burning of agricultural residues emits CH₄ and N₂O. The quantity of crop residue burning in Canada can be estimated as follows:

Equation A3.4–34

$$Q_{BURN} = \sum_T (PRODUCTION_T \times (1 - MOISTURE_T) \times RatioAR/P_T \times PCB_T \times RATIO_{SCALE})$$

Q_{BURN}	=	quantity of crop residue burned from crop T for each province, Mg dry matter yr ⁻¹
$PRODUCTION_T$	=	total production of crop T, Mg yr ⁻¹
$MOISTURE_T$	=	moisture content of the product from crop T, fraction
$RatioAR/P_T$	=	ratio of above-ground crop residue to the crop product for crop T, unitless
PCB_T	=	percent of crop residue that is subject to field burning for crop T, fraction
$RATIO_{SCALE}$	=	a scaling factor or an intensity factor adjusted for burning in 2006, unitless

Data collected in 2001 and 2006 by Statistics Canada through its Farm Environmental Management Survey (FEMS)²⁶ include crop residue burning. The type of crop and the extent of crop residue burning for each province were only available for 2006; these data were collected in FEMS and are summarized in Table A3.4–42. To establish a complete time series of activity data, additional information on crop residue burning for 1991 and 1996 has been gathered through expert consultations (Coote et al., 2008). Thus, a crop that was subject to field burning in 2006 was also assumed to be subject to field burning for the entire time series.

The intensity of crop residue burning in each province for 1991, 1996 and 2001 was adjusted as a ratio based on the average burning for 2006. Janzen et al. (2003) report basic characteristics of crops, such as moisture content of crop product and ratio of aboveground crop residue to crop product. Annual production of each crop subject to residue burning is available (Statistics Canada, n.d. [g]). Other parameters, such as fraction of biomass actually burned, and emission factors required for emission estimates, were obtained from the 2006 IPCC Guidelines.

26 Available at <http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5044>.

Table A3.4–42 Burning of Crop Residues by Crop Types in 2006

	Spring Wheat	Winter Wheat	Oats	Barley	Mixed Grains	Flaxseed	Canola
% of Crop Residue Burned (by Weight)							
AB	0	0	0	0	0	8	0
BC	0	0	0	0	0	0	0
MB	2	3	3	1	0	17	1
NB	0	0	1	0	0	0	0
NL	0	0	0	0	0	0	0
NS	33	0	0	0	0	0	0
ON	0	0	0	1	2	0	0
PE	3	0	0	1	0	0	0
QC	0	0	1	0	0	0	0
SK	0	0	0	0	0	15	1

Table A3.4–43 Crop Residue Burning by Province in Canada for 1991, 1996, 2001 and 2006

	1991 ^a	1996 ^a	2001 ^b	2006 ^b
	% of Crop Residue Burned (by Weight)			
AB	0.8	0.7	0.2	0.2
BC	0	0	0	0
MB	12.6	10.1	8.9	2.3
NB	0.5	0.5	0.5	0.5
NL	0	0	0	0
NS	0.5	0.5	0.5	0.5
ON	0.7	0.7	0.7	0.3
PE	0.4	0.4	0.4	0.4
QC	0.4	0.4	0.4	0.3
SK	8.1	5.8	3.9	1.5

Note:

a. Data were gathered through consultations by Coote et al. (2008).

b. Data extracted from FEMS (2001) and (2006), collected by Statistics Canada.

N_2O and CH_4 emissions from crop residue burning are estimated using the following equation:

Equation A3.4–35

$$\text{EMISSION}_{\text{BURN}} = \sum(Q_{\text{BURN},i} \times C_F \times G_{EF})/1000$$

$\text{EMISSION}_{\text{BURN}}$	=	emissions of N_2O or CH_4 from the burning of crop residues for Canada (kt N_2O or CH_4)
$Q_{\text{BURN},i}$	=	quantity of crop residue burned from province i , Mg, dry matter yr^{-1}
C_F	=	fuel efficiency (IPCC, 2006), unitless
G_{EF}	=	emission factor (IPCC, 2006), 0.00007 kg N_2O or 0.0027 kg $\text{CH}_4 \text{kg}^{-1}$ of dry matter burned
1000	=	converting Mg to kt

A3.4.8. CO_2 Emissions from Liming and Urea Fertilization

A3.4.8.1. CO_2 Emissions from Liming

Limestone (CaCO_3) is often used to neutralize acidic soils, increase the availability of soil nutrients, in particular phosphorus, reduce the toxicity of heavy metals and improve the crop growth environment. During this neutralization process, CO_2 is released in bicarbonate equilibrium reactions that take place in the soil.

The rate of CO_2 release varies with soil conditions and the types of compounds applied. In most cases, lime is applied repeatedly. Thus, for the purposes of the inventory, it is assumed that the annual rate of lime is in near equilibrium with the consumption of lime in previous years. Emissions associated with lime application are calculated from the amount of lime applied annually.

The amount of C released from limestone/dolomite application is calculated using the default IPCC Tier 1 approach (IPCC, 2006).

$$\text{CO}_2 - \text{C Emission} = \sum(M_{\text{Limestone/dolomite},i} \times EF_{\text{Limestone/dolomite}})$$

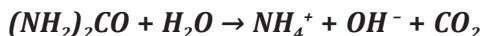
CO_2 -C Emission	=	annual C emissions from lime application, Mg C yr ⁻¹
$M_{\text{Limestone/dolomite},i}$	=	annual amount of limestone and dolomite consumption in province i , Mg yr ⁻¹
$EF_{\text{Limestone/dolomite}}$	=	0.12, limestone emission factor or 0.13 dolomite emission factor

The quantity of lime and dolomite used for agricultural purposes is not collected through the COA by Statistics Canada, but rather through Natural Resources Canada's *Canadian Minerals Yearbook* (1990 to 2006). For more recent years, this information is only available on request.²⁷ This data source provides a consistent and complete time series of activity data on agricultural lime consumption in Canada. As this data source provides no information on the ratio of dolomite to limestone, the ratio from data collected through consultation with the Canadian Fertilizer Institute was used.

The 95% confidence limits associated with annual lime consumption data were estimated to be $\pm 30\%$. This uncertainty was assumed to include the uncertainty of lime sales, the uncertainty of when lime sold is actually applied, and thus the uncertainty in the timing of emissions. The uncertainty in the emission factor was assumed to be -50% based on the 2006 IPCC Guidelines.

A3.4.8.2. CO_2 Emissions from Urea Fertilization

When urea or urea-based N fertilizer is applied to soil to augment crop production, CO_2 is released upon hydrolysis as follows:



In addition to urea, Canadian farmers also use significant amounts of urea ammonium nitrate (28-0-0) with a mixture of 30% $(NH_2)_2CO$. Carbon dioxide emissions from urea fertilization can be estimated using Equation A3.4–37:

$$\text{CO}_2 - \text{C Emission} = \sum(M_{\text{Urea},i} \times EF_{\text{Urea}})$$

CO_2 -C Emission	=	annual C emissions from urea application, Mg C yr ⁻¹
$M_{\text{Urea},i}$	=	annual amount of urea fertilization, Mg yr ⁻¹
EF_{Urea}	=	0.20, emission factor

Statistics Canada collects and publishes annual fertilizer shipment data, including urea and urea ammonium nitrate (Statistics Canada, n.d. [h], Statistics Canada, n.d. [i]). The uncertainty estimate associated with the emissions is assessed based on simple error propagation using survey uncertainty of $\pm 15\%$ for the activity data and an uncertainty of -50% associated with the EF specified in the 2006 IPCC Guidelines.

²⁷ [NRCan] Natural Resources Canada. 2007–2016. Canada, Production of Limestone – Stone. Unpublished data. Natural Resources Canada, Mineral & Mining Statistics Division.

A3.5. Methodology for the Land Use, Land-Use Change and Forestry Sector

The Land Use, Land-Use Change and Forestry (LULUCF) sector of the inventory includes estimates of greenhouse gas (GHG) emissions and removals associated with managed lands and with the conversion of land from one category to another.

As in Chapter 6, the structure of this annex attempts to maintain the land-based reporting categories, while grouping related data collection and estimate development methodologies. Section A3.5.1 summarizes the spatial framework for estimate development and area reconciliation. The general approach for estimating carbon (C) stock changes, emissions and removals in all forest-related categories, including Forest Land, Forest Land converted to other land uses and Land Converted to Forest Land, is briefly described in section A3.5.2; this description is not repeated under the Forest Land Converted to Cropland, Forest Land Converted to Wetlands and Forest Land Converted to Settlements subcategories. Section A3.5.3 describes the approach for estimating emissions associated with the use and disposal of harvested wood products (HWP) from wood harvested in Canada and section A3.5.4 describes the methods used to quantify the effect of management practices on agricultural land for the Cropland category. Likewise, the sections on the Grassland (A3.5.5), Wetlands (A3.5.6) and Settlements (A3.5.7) categories focus on category-specific estimation methodologies.

A3.5.1. Spatial Framework for LULUCF Estimate Development and Area Reconciliation

Canada's monitoring system for LULUCF draws on the close collaboration among several scientists and experts in different disciplines. Early on, it was recognized that the approaches, methods, tools and data that are available and most suitable for monitoring human activities in one land category are not always appropriate for another. Differences exist in the spatial framework specific to each land category, and these differences create a risk that activity data and estimates would be spatially inconsistent. A hierarchical spatial framework was agreed upon by all partners contributing to the LULUCF sector to ensure the highest possible consistency and spatial integrity of inventory estimates.

The LULUCF sector of the GHG inventory reports information in 18 reporting zones (Chapter 6, Figure 6–1). These reporting zones are essentially the same as the ecozones of the National Ecological Framework, a hierarchical, spatially consistent national ecosystem classification (Marshall et al., 1999). For the purpose of reporting LULUCF estimates, three ecozones are split into smaller land units: the Boreal Shield and Taiga Shield ecozones are split into their east and west components to form four reporting zones, and the Prairies ecozone is divided into a semi-arid and a subhumid component (McGovern, 2014). These subdivisions do not alter the hierarchical nature of the spatial framework.

Analysis units are the finest level of spatial resolution and are specific to each estimation system. In managed forests, the analysis units are the geographic intersection of reporting zones (Chapter 6, Figure 6–1) and provincial/territorial forest management units. For the purpose of this assessment, managed forests were classified into 607 analysis units across 12 provinces and territories; Nunavut was excluded because there is no managed forest area in this northern region (Table A3.5–1). Changes in the number of spatial analysis units may occur from one submission to the next and reflect refinements in the integration of multiple spatial layers. For example, the modification of administrative boundaries, timber areas and parks can result in units that do not meet the criteria for separate analysis; these units are therefore regrouped.

Table A3.5–1 Spatial Analysis Units of Managed Forests

Province/Territory	Number of Analysis Units
NL	24
PE	1
NS	1
NB	1
QC	129
ON	52
MB	70
SK	40
AB	181
BC	65
YT	13
NT	30
NU	0
Canada	607

The most suitable spatial framework for GHG monitoring of cropland are the polygons of the Soil Landscapes of Canada²⁸ (SLC). A soil landscape describes a group of soils and their associated landscapes and provides information, such as surface form, slope, typical soil C content under native and dominant agricultural land use, and water table depth. Soil landscapes are spatially associated with SLC polygons (the analysis units) that may contain one or more distinct soil landscape components. SLC polygons are also the basic units of Canada's National Ecological Framework, a hierarchical, spatially consistent national classification system within which ecosystems of various scales can be described, monitored and reported on (Marshall et al., 1999). The 12 353 SLC polygons are nested in the next level of generalization (1027 ecodistricts), which are further grouped into 194 ecoregions and 15 ecozones. SLC polygons span in the order of 1000 to 1 000 000 hectares (ha) and are appropriate for mapping at the scale of 1:1 million.

Analysis units for estimating the areas of forest converted to other land uses are the result of the spatial intersection of forest conversion strata (Figure A3.5–7) with ecological and administrative boundaries. Forest conversion strata were developed on the basis of expected conversion rates and characteristics. The sampling approach used to monitor forest conversion requires analysis units to be as consistent as possible with respect to the patterns of forest conversion and large enough to provide an acceptable sample size, given the predetermined sampling rate.

The analysis units of different land-use categories can overlap. Most often, the exact location of events within a unit is not known. Therefore, the activity data pertaining to different land-use categories cannot be harmonized at the level of analysis units. The spatial harmonization is conducted within 60 reconciliation units (RUs), which are derived from the spatial intersection of reporting zones with provincial and territorial boundaries. Quality control and quality assurance procedures are conducted at the level of analysis units during estimate development and at the level of RUs during estimate compilation.

The total land mass of Canada reported in CRF table 4.1 is estimated using geomatics layers based on the SLC polygons and quality checked using data from the National Atlas²⁹, and it includes land area (estimated as 906 676.55 kha) and area covered by fresh water (estimated as 89 680.51 kha). Total national area sources vary for Canada depending on the data source, but as the SLC polygons are the base layer for the Ecological Framework of Canada, this data source is considered the most appropriate for consistency within LULUCF.

A3.5.2. Forest Land and Forest-related Land-Use Change

A3.5.2.1. Carbon Modelling

The estimation of C stock changes, emissions from and removals by managed forests, forest conversion to other land uses and land converted to forest land is conducted with version 3 of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al., 2009), the most recent of a family of models whose development dates back to the late 1980s (Kurz et al., 1992). The model integrates forest inventory information (stand age, area and species composition), curves of merchantable volume over age, equations to convert stand merchantable volume into total biomass, data on natural and anthropogenic disturbances, and simulations of C transfers between pools and exchanges with the atmosphere that are associated with ecosystem processes and various events.

The ecosystem processes modelled by the CBM-CFS3 to generate the estimates submitted in this report are growth, litterfall, non-disturbance tree mortality and decomposition. The CBM-CFS3 also models events, such as management activities, forest conversion and natural disturbances. Management activities represented are clear-cut, shelterwood harvest, seed tree harvest, selection harvest, commercial thinning, precommercial thinning, salvage logging, residential firewood collection and the burning of harvest residues. Different practices of forest conversion are also simulated, including controlled burning.

The forest C pools represented in the CBM-CFS3 can be matched with the Intergovernmental Panel on Climate Change (IPCC) forest C pools (Table A3.5–2). Although not shown here, living biomass pools are further subdivided into two sets, for each of hardwood and softwood tree species.

Annual ecosystem process events are simulated as C transfers between C pools executed at each time step (annually) in every inventory record (Figure A3.5–1). During annual processes, C is taken up in the biomass pool and some biomass C is transferred to dead organic matter (DOM) pools. The decay of DOM results in C transfer to another DOM pool (e.g., stem snags to medium deadwood pool), to a slow soil pool or to the atmosphere. More information on pool structure and decay rates is provided in Kurz et al. (2009). Rates of C transfer are defined for each pool, based on pool-specific turnover rates (for biomass pools) or decay rates (DOM and soil pools). Turnover rates can be either very high (e.g., 95% for hardwood foliage) or very low (e.g., < 1% for stemwood). Annual decay rates are defined for a reference mean annual temperature of 10°C and exhibit temperature sensitivity according to defined Q₁₀ relationships; the decay rates vary between 50% (very fast DOM pools, such as dead fine roots) and 0.0032% (slow soil pool).

28 Available online at <http://sis.agr.gc.ca/cansis>.

29 Available online at: <https://www.nrcan.gc.ca/maps-tools-and-publications/maps/atlas-canada/10784>.

Growth is simulated as an annual process. Each of the records (roughly 3 million) in the 607 analysis units of the forest inventory is associated with a yield curve that defines the dynamics of gross merchantable volume over time. Assignment of an inventory record to the appropriate curve is based on a classifier set that includes province, ecological stratum, leading species, site productivity class and several other classifiers that differ between provinces and territories. Curve libraries for each province and territory in Canada are similar to those used by resource management agencies in the forest planning processes and are derived from permanent or temporary sample plots or from forest inventory information.

Table A3.5-2 Forest Carbon Pools in IPCC and CBM-CFS3

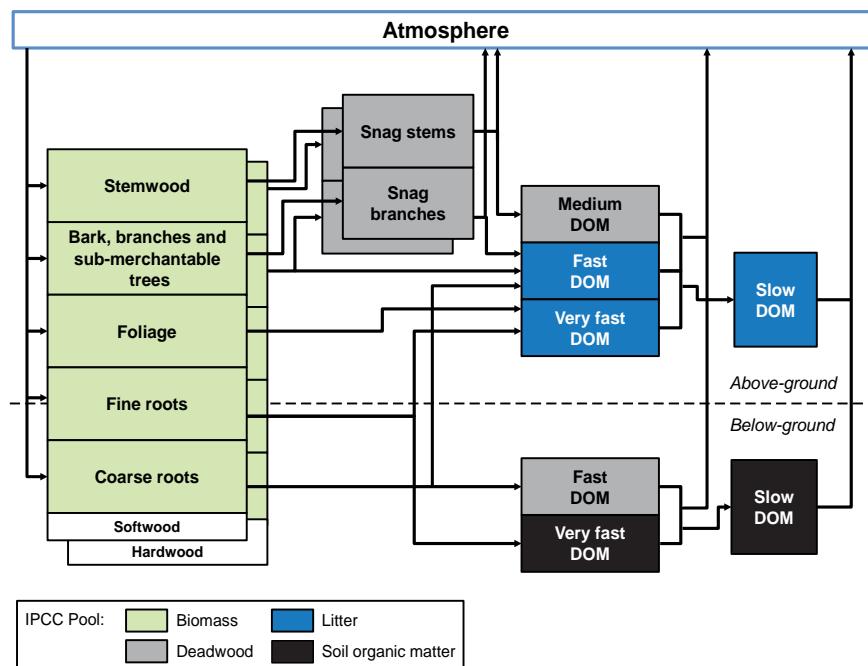
IPCC Carbon Pools		Pool Names in CBM-CFS3
Living Biomass	Above-ground biomass	Merchantable stemwood Other (submerchantable stemwood, tops, branches, stumps, non-merchantable trees) Foliage
	Below-ground biomass	Fine roots Coarse roots
Dead Organic Matter (DOM)	Deadwood	Above-ground fast Below-ground fast Medium Softwood stem snag Softwood branch snag Hardwood stem snag Hardwood branch snag
	Litter	Above-ground very fast Above-ground slow
Soils	Soil organic matter	Below-ground very fast ^a Below-ground slow Black carbon ^b Peat ^b

Notes:

a. Below-ground very fast pool includes dead and decaying fine roots, which in practice cannot be separated from soil.

b. Black carbon and peat are currently not estimated.

Figure A3.5-1 Carbon Pools and Transfers Simulated by the CBM-CFS3



Note: Source = White et al. (2008)

Conversion of gross merchantable volume curves to above-ground biomass curves is performed with a set of equations developed for Canada's National Forest Inventory (Boudevyn et al., 2007). These equations derive the above-ground biomass of each stand component from merchantable stemwood volume (per ha), for each province/territory, ecozone, leading species or forest type. Finally, below-ground biomass pools are estimated using regression equations (Li et al., 2003). Mean annual increments are not used in this derivation.

Modelling of C transfers triggered by disturbances is based on the disturbance type and severity, the forest ecosystem affected and the ecological region. For modelling purposes, different practices of forest conversion are also implemented as disturbances. The impact of a disturbance is represented by a disturbance matrix, which specifies, for one or more disturbance types, the proportion of C in each ecosystem pool that is transferred to other pools, released to the atmosphere or transferred to the HWP pool (Figure A3.5–2). In the current submission, the simulation uses a total of 191 disturbance matrices. The number of different disturbance matrices is dependent on the availability of activity data (e.g., the spatial and temporal resolution of disturbance data) and on the knowledge required to parameterize the matrices for more distinct regions or intensities of disturbance.

Within disturbed lands, the amount of C emitted as CO₂ from each pool at the time of disturbance, documented in each disturbance matrix, can be specific to the pool, the types of forest and disturbance intensity, and the ecological zone. There are therefore no CO₂ emission factors applicable to all disturbances of a given type, such as fires. With a few exceptions, the proportion of total C emitted in each C-containing GHG (CO₂, CO and CH₄) due to fire is constant: 90% of C is emitted as CO₂, 9% as CO and 1% as CH₄ (Cofer et al., 1998; Kasischke and Bruhwiler, 2003).

Carbon emissions emitted as CO oxidize in the atmosphere resulting in indirect CO₂ emissions. Amounts of C emitted as CO and indirect CO₂ are calculated by multiplying total C by, respectively, 28/12 and 44/12. More details on the reporting of these indirect CO₂ emissions can be found in Chapter 6 and Annex 7.

While the CBM-CFS3 can model C fluxes at various spatial scales, generating national estimates involves harmonizing, integrating and ingesting vast quantities of data from a large variety of sources. Section A3.5.2.3 documents the key data sources used for this submission.

Figure A3.5–2 Disturbance Matrix Simulating the Carbon Transfers Associated with Clear-Cut Harvest and Salvage Logging Applicable in All Ecozones Except Those in Alberta and Quebec

	73	74	75	76	77	78	79	7A	7B	Products
1. Softwood merchantable				0.15						0.85
2. Softwood foliage	1									
3. Softwood others			1							
4. Softwood sub-merchantable			1							
5. Softwood coarse roots			0.5	0.5						
6. Softwood fine roots	0.5	0.5								
7. Hardwood merchantable					0.15					0.85
8. Hardwood foliage	1									
9. Hardwood other			1							
10. Hardwood sub-merchantable			1							
11. Hardwood coarse roots			0.5	0.5						
12. Hardwood fine roots	0.5	0.5								
13. Above-ground very fast soil C	1									
14. Below-ground very fast soil C		1								
15. Above-ground fast soil C			1							
16. Below-ground fast soil C				1						
17. Medium soil C					1					
18. Above-ground slow soil C						1				
19. Below-ground slow soil C							1			
20. Softwood stem snag					0.5					0.5
21. Softwood branch snag		1								
22. Hardwood stem snag					0.5					0.5
23. Hardwood branch snag			1							
24. Black C							1			
25. Peat								1		

A3.5.2.2. Forest drainage

Forest drainage is used to lower the water table, thereby improving soil aeration and promoting root development and tree growth on low-productivity organic soils. A consultation with forestry industry experts and an extensive literature review carried out in 2015 and 2016 suggested that the only province in Canada where operational drainage of organic soils for forestry occurred was Quebec (Gillies, 2016). This management activity occurred from the 1980s through to the mid-2010s on a small percentage of peatlands corresponding to three RUs (11, 12 and 15) on both private and public lands. Forest drainage has progressively declined since 2003 due to the end of government subsidies and changes to Quebec's forest management tenure.

Data on forest drainage were compiled from a combination of historical documents, expert consultations and provincial statistics to develop a time series from 1980–2018 of annual peatland areas drained for forestry on both private and publicly owned forests of Quebec. Provincial statistics (Gouvernement du Québec, 2018) were reported by administrative region (AR) for 1994–2008 and by province for 1986–1993 and for 2009–2017. Drainage data for 1980–1985 were assumed to be constant, resulting in a cumulative area drained equivalent to the 1986 value reported by Quebec statistics, which was also consistent with values cited in Hillman (1987). Given the absence of drainage activity data for 2018 (Gouvernement du Québec, 2018) and the fact that there were no areas drained in 2016 and 2017, drained areas were assumed to be zero after 2017. Estimates of drained areas by AR (1994–2008) were allocated to the three RUs by overlaying the AR to create a spatially weighted area average that was applied to the provincial values for all years.

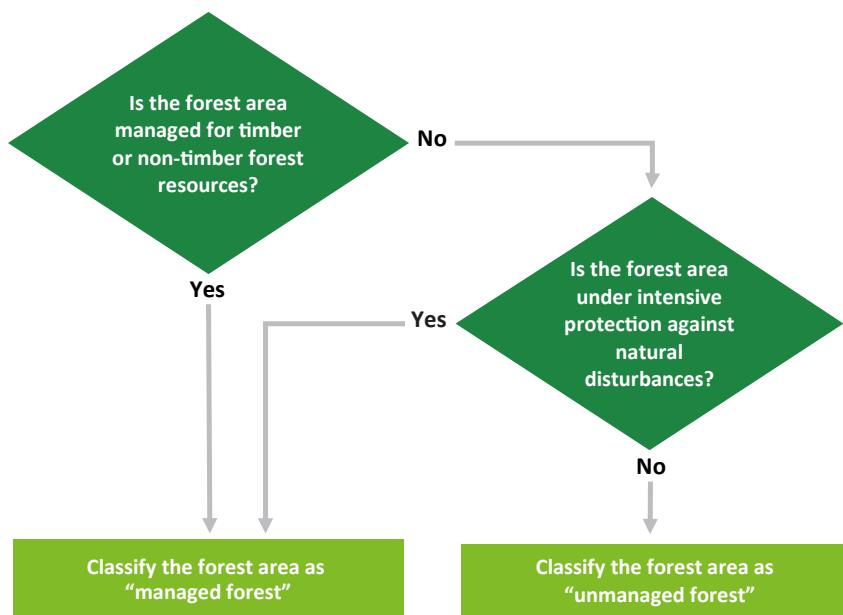
Emissions of CO₂, CH₄ and N₂O from drained organic soils were calculated using a Tier 1 method and emission factors from Tables 2.1, 2.2 and 2.3, respectively, of the 2013 Wetland Supplement to the 2006 IPCC Guidelines (IPCC, 2014). Emission factors are associated with the temperate (RUs 11 and 12) and boreal (RU 15) climate zones. The fraction of area covered by ditches was also determined using the default values for drainage ditches from Table 2.3 of the 2013 Wetland Supplement (IPCC, 2014).

A3.5.2.3. Data Sources

Managed Forest Land

Canada's forests are classified as "managed" or "unmanaged" based on the occurrence of management activities for timber or non-timber and on the level of protection against disturbances (Figure A3.5–3). Managed forests occur within all provinces and territories of Canada, with the exception of Nunavut (Figure A3.5–4). The estimation of the managed forest area required the spatial delineation and combination of boundaries of many different forest areas, including all operational forest management units, timber supply areas, tree farm licences, industrial freehold timberland, private woodlots and

Figure A3.5–3 Decision Tree for the Determination of Managed Forest Area



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any other land in the Forest Land category where there is active management for timber or non-timber resources, as well as forest areas where there is intensive protection against natural disturbances. All these layers are aggregated and intersected with underlying forest inventory data. The procedures are documented in Stinson et al. (2011).

The model tracks managed forest lands disturbed by harvesting before and after 1990, lands affected by various natural disturbances since 1990 and lands not affected by any disturbances since 1990. Lands not affected by disturbances since 1990 are broken down into stands originating after harvesting or following stand-replacing wildfires prior to 1990. All areas of land in 1990 that were not identified as being of harvest origin were assumed to be of wildfire origin (given that insect disturbances are not stand replacing). These distinctions are used to separate stands dominated by anthropogenic and natural emissions and removals (see Kurz et al., 2018 and section A3.5.2.4).

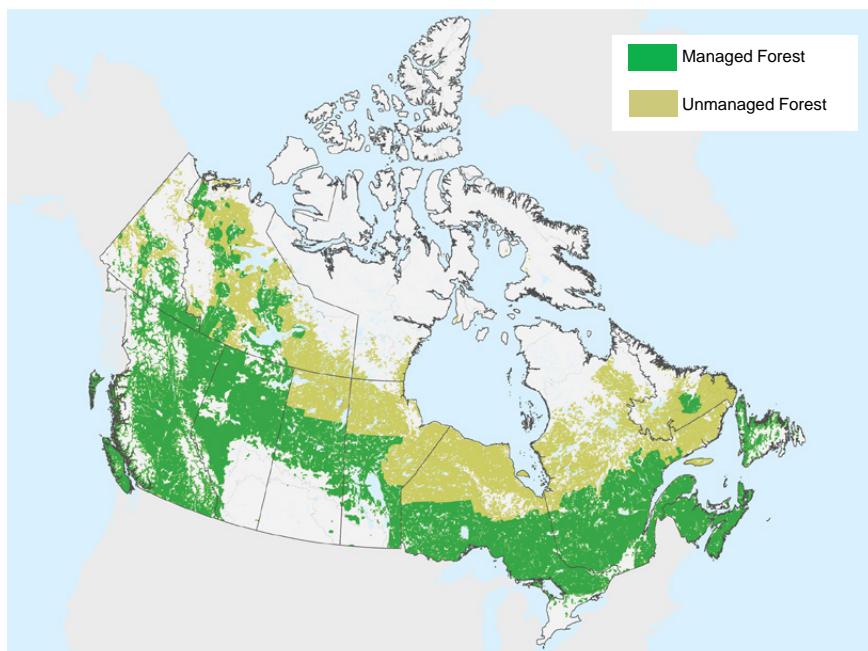
Forest management activities are documented in the National Forestry Database³⁰ and additional information on specific activities is obtained directly from provincial and territorial forest management agencies. The Canadian provincial and territorial governments, whose jurisdiction includes natural resource management, provide essential information—notably detailed forest inventory data, details on forest management activities and practices, disturbance information including prevention or control, regional yield tables (volume/age curves), site indices—and regional expertise (Table A3.5–3). The forest inventory data in Canada's National Forest Inventory (CanFI 2001) were used for New Brunswick, Manitoba, Saskatchewan, Yukon and the Northwest Territories. More recent and higher-resolution inventory data were provided by Prince Edward Island, Newfoundland and Labrador, Nova Scotia, Quebec, Ontario, British Columbia and Alberta. A series of “method papers” describe the compilation process for each provincial and territorial forest inventory. Since forest inventory data were not collected in the same years, additional steps were necessary to synchronize the inventory data to the year 1990 (Stinson et al., 2011).

Activity data for the burning of harvest residues are obtained from the National Forestry Database for all regions except specific areas of British Columbia where expert opinion is used.³¹ While in British Columbia these data refer to slash burning of harvest residues (broadcast, slash pile burning or a combination of both), in other regions of Canada they may also include prescribed burning for fuel control.

30 National Forestry Database, available online at <http://nfdp.ccfm.org/en/index.php>

31 In British Columbia, expert opinion indicates that the proportion of areas harvested using clear-cut where slash burning is applied is 15% on the coast and 50% for the rest of the province.

Figure A3.5–4 **Lands with Managed and Unmanaged Forests in Canada**



Collection of firewood for residential heating is a common practice in Canada, with an estimated 93% of annual firewood taken from forested lands and the rest from agricultural woodlands and urban trees. To estimate the impact of this activity on the C balance of Canadian forests a set of rules was developed to disaggregate these volumes into several components (Hafer et al., 2020, Doyon et al., 2019): softwood, hardwood and mixedwood collected from forested lands, woody biomass collected from croplands, urban trees from settlement lands, pellets and manufactured logs (the latter four components modelled under HWP, see A3.5.3). For the forested-land target components and based on survey data, a list was developed for the spatial analysis units within each RU from which the firewood to be collected should be taken.

Regional firewood harvest practices in Canada and regionally-differentiated disturbance matrix parameters were implemented in the CBM-CFS3 model for three conceptual ‘firewood collection zones’: (i) Mixedwood-Acadian (MWA), comprised of the Atlantic Maritime and Mixedwood Plains ecozones; (ii) agricultural (AGR), comprised of the Subhumid- and Semi-arid Prairie ecozones; and (iii) boreal-montane (BOR), comprised of all other forest ecozones. Firewood collection in

Table A3.5–3 Main Sources of Information and Data, Managed Forests

Description	Source	Spatial Resolution	Temporal Coverage	Reference
Climate data	CFS	Analysis units	1961–1990 normals	McKenney et al. (2001)
Forest inventories & merchantable volume data ^a	Canada's National Forest Inventory (CanFI)	CanFI grid cell	1949–2004	https://nfi.nfis.org/index.php
	NL	Analysis units	1991–2006	Provincial experts
	PE	Analysis units	2000	Provincial experts
	NS	Analysis units	2006	Provincial experts
	QC	Analysis units	2000	Provincial experts
	ON	Analysis units	2000	Provincial experts
	AB ^b	Analysis units	1949–1999	Provincial experts
	BC	Analysis units	2011	Provincial experts
Conventional harvest data ^c	National Forestry Database	Provincial boundaries	1990–2019	http://nfdp.ccfm.org/
Slash burning	National Forestry Database, for jurisdictions other than BC	Provincial boundaries	1990–2020	http://nfdp.ccfm.org/
	National Forestry Database and BC	Sub-provincial boundaries	1990–2020	Provincial experts and http://nfdp.ccfm.org/
Residential firewood harvest data	Energy Sector data for residential firewood use	Reconciliation Units	1990–2020	Sections A3.1.4.1 and A3.5.3
Industrial fuelwood data	Energy Sector data for industrial fuelwood use	Provincial boundaries	1990–2019	Sections A3.1.4.1 and A3.5.3
Insect data	Forest Insect and Disease Survey	Spatially explicit	1990–2017	Atlantic Forestry Centre and Pacific Forestry Centre
	NL	Spatially explicit	2000–2003	Provincial experts
	QC	Spatially explicit	1990–2020	Provincial experts; https://www.donneesquebec.ca/recherche/fr/dataset/donnees-sur-les-perturbations-naturelles-insecte-tordeuse-des-bourgeons-de-lepinette
	MB	Spatially explicit	1990–2020	Provincial experts and provincial forest health aerial overview surveys; National Forest Pest Strategy Information System
	SK	Spatially explicit	1985–2013	Provincial experts; National Forest Pest Strategy Information System
	AB	Spatially explicit	1990–2020	Provincial experts; Alberta Forest Health Aerial Overview
	BC	Spatially explicit	1990–2020	Provincial experts; BC Forest Insect and Disease Survey; BC Aerial Overview Survey
	YT	Spatially explicit	1994–2018	Provincial experts; Yukon Forest Health Aerial Overview
	NT	Spatially explicit	1990–2020	Provincial experts; Northwest Territories Forest Health Survey
Fire data	National Burned Area Composite	Spatially explicit	1990–2020	http://www.nrcan.gc.ca/node/13159
Drainage data ^d	QC	Province of Quebec boundaries	1980–1985	Provincial experts; historical records; Hillman (1987); Gillies (2016)
	Ministère des Forêts, de la Faune et des Parcs du Québec	Province of Quebec boundaries	1986–1994	https://mffp.gouv.qc.ca/les-forets/connaissances/statistiques-forestieres
	Ministère des Forêts, de la Faune et des Parcs du Québec	Administrative regions of Quebec	1994–2008	https://mffp.gouv.qc.ca/les-forets/connaissances/statistiques-forestieres
	Ministère des Forêts, de la Faune et des Parcs du Québec	Province of Quebec boundaries	2008–2018	https://mffp.gouv.qc.ca/les-forets/connaissances/statistiques-forestieres
Notes:				
a.	Forest inventory and merchantable wood volume yield data were obtained from Canada's National Forest Inventory and/or from provincial experts where specified.			
b.	Alberta's forest inventory database comprises provincial forest inventory for the province's Forest Management Areas, and CanFI inventory for the remainder of the managed forest landbase.			
c.	Given the absence of complete harvest data for the most recent reporting year for all provinces and territories, 2020 harvest data are estimated by assuming them to be equal to 2019 values.			
d.	No new drainage activity data have been registered in the Province of Quebec since 2016.			

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both the MWA and AGR zones is assumed to be via light thinning (30% removal), while firewood collection in the BOR zone is assumed to be via clear-cut harvesting (85% removal). Inventory records selected for firewood collection are disturbed in decreasing order of total snag content, to ensure that a reasonable (though unspecified) proportion of the firewood is collected as dead wood

Data on biomass used as residential firewood are obtained from surveys of residential wood use and origin. Sections A3.1.4.1.4 and A3.5.3 of the present report provide additional information on these surveys and the methodology used to convert the consumption and use data collected to volumes of firewood. Areas specifically attributed to firewood harvest are defined by the model based on those volume estimates.

Areas disturbed by wildfires were extracted from the Canadian Wildland Fire Information System's National Burn Area Composite (NBAC) for the years 1990 to the current inventory year (Table A3.5–3). The NBAC is a composite of low- and medium-resolution remote sensing data and fire mapping data prepared by the Canadian Forest Service and combined with data provided by resource management agencies from across Canada. The NBAC provides a complete mapping of wildfires using medium-resolution remote sensing data when available; data from resource management agencies are given second priority; and low-resolution remote sensing data are used only where no other fire mapping data are available.

Insect disturbances are monitored by aerial surveys (Table A3.5–3), which record the area impacted by the disturbance and assign an impact severity class that indicates the degree of tree mortality or defoliation. The area of impact is assigned to the appropriate analysis unit and host species within it, and the severity of the impact is reflected in the parameters of the disturbance matrix applied (Kurz et al., 2009).

Areas drained for forestry (Table A3.5–3) on private and publicly owned forests in Quebec are estimated using historical documents, consultations and Quebec statistics. Spatial allocation by RU was performed using Quebec statistics.

A3.5.2.4. Quantifying Anthropogenic Emissions and Removals

Interannual variations and trends in emissions and removals from managed forests in Canada are dominated by the impact of wildfires and periodic forest insect outbreaks, making it difficult to detect trends due to human actions in the forest (Kurz et al., 2008a, 2018; Stinson et al., 2011; Kurz et al., 2013).

The IPCC does not currently provide default methods for separating anthropogenic emissions and removals from those occurring due to natural disturbances, although it has recognized the issues of reporting emissions from natural disturbances for some countries (IPCC, 2010). Furthermore, the IPCC (2010) has encouraged countries that use Tier 3 methodologies to work towards the development of new approaches that can improve the identification of anthropogenic emissions and removals. The CBM-CFS3 model now has the capability to track and separate emissions and removals in managed forest stands dominated by the impact of anthropogenic activities from those in which emissions and removals result from a significant uncontrollable natural disturbance that has masked the legacy of human management and affected the commercial value of the stand.

Forest fires are tracked in the natural disturbance component because human-caused ignitions are responsible for a small proportion of the area burned in Canada (~10% of the area burned; Hanes et al., 2019) and the role of humans is uncertain in explaining the increase or decrease of area burned. Forest fires have been an integral part of the Canadian landscape for millennia. While fire regimes are driven by complex interactions between climate (through temperature, moisture and wind), fuel and humans (as agents of ignition and fire suppression), recent research has shown that climatic drivers mostly control burned areas in northern temperate and boreal forests of eastern Canada and lead to extreme fire events regardless of human-caused ignitions (Danneyrolles et al., 2021). The dominance of climate drivers has also been demonstrated in temperate and boreal forests of western North America (Holden et al., 2018; Gaboriau et al., 2020), and fuel moisture has been suggested as the most critical driver of burned areas and extreme fire events at the global scale (Bowman et al., 2017; Kelley et al., 2019). About 3% of fires in Canada are responsible for 97% of the area burned (Stocks et al., 2002) and generally occur on just a few critical days with extreme weather conditions conducive to fire (Wang et al., 2017). These fires are mostly caused by lightning and largely occur in remote areas where fire detection and suppression systems are often delayed, compared with human-caused fires that generally occur in more populated, full-suppression zones.

Because direct human actions can be negative and positive, both as agents of ignition (accidentally or intentionally for management activities) and by actively suppressing fires and controlling fuel, their effects on area burned are difficult to quantify and separate from other drivers. The current default assumption that human activity is having neither a positive nor a negative impact on the natural fire regime across the country avoids introducing a bias that would not be supported by long-term data and scientific understanding. Although this methodology separately tracks land areas that are dominated by either natural or anthropogenic influences, the evolving balance between those areas over time will capture long-term trends in the natural fire regime in managed forest areas.

This reporting approach ensures that emissions from stands affected by uncontrollable natural disturbances and the subsequent removals by the regrowth of these stands are tracked separately from commercially mature managed stands, allowing for improved differentiation of emissions and removals associated with direct forest management actions from non-anthropogenic emissions and removals occurring due to natural disturbances.

The management and natural disturbance history of each individual stand (inventory record) in the managed forest area is used to assign stands to two groups. Emissions and removals are identified as being anthropogenic when (i) a stand's growth trajectory has been significantly modified by human intervention—this definition includes commercial clear-cut and partial harvest, commercial and pre-commercial thinning, salvage logging, site preparation, and rehabilitation and planting on stands that have undergone both stand replacement and partial natural disturbances; and (ii) regardless of its origin, a stand has attained commercial maturity and therefore is actively considered within forest management planning scenarios (eligible to be scheduled for harvest). Once a stand originating from natural disturbance has reached this age, emissions and removals are switched to the reported category.

In contrast, emissions and removals resulting from natural disturbance are defined as originating from (i) stands that have been affected by a stand-replacing natural disturbance up to the period that stands reach commercial maturity, or (ii) stands that have been affected by partial disturbance resulting in reduced standing biomass until that stand has attained pre-disturbance equivalent biomass. Only partial disturbances causing more than 20% mortality are included in the natural disturbance category.

In the initial implementation of this approach in the 2017 NIR, a fixed value of 60 years was assumed to be generally applicable to represent a minimum return period to commercial maturity across Canada. Since the 2018 NIR, regionally specific return periods based on differences in forest management practices, species distributions and stand dynamics among regions have been used.

To develop regionally representative definitions of commercial maturity, a questionnaire was distributed to provinces and territories in March 2017. The objective of this consultation process was to document forest management practices across Canada, with a focus on the treatment of naturally disturbed forest stands in operational planning. As such, work with provincial experts provided a minimum return period to commercial maturity ranging from 45 to 99 years, with an average of 76 years. In most cases, provincial agencies defined species-specific commercial maturity based on the maximum mean annual increment of species-specific yield curves for a high productivity site class in a given region. Other provincial agencies used empirical data based on observed regional minimum harvest ages or an age to achieve a specific piece size. Based on the species-specific commercial age, a weighted minimum return period was determined for each reporting zone using the proportional breakdown of the commercial species that were attributed a minimum operable age, or minimum harvest age, in that area. Greater detail on the methodological approach used to track anthropogenic emissions and removals can be found in Kurz et al. (2018).

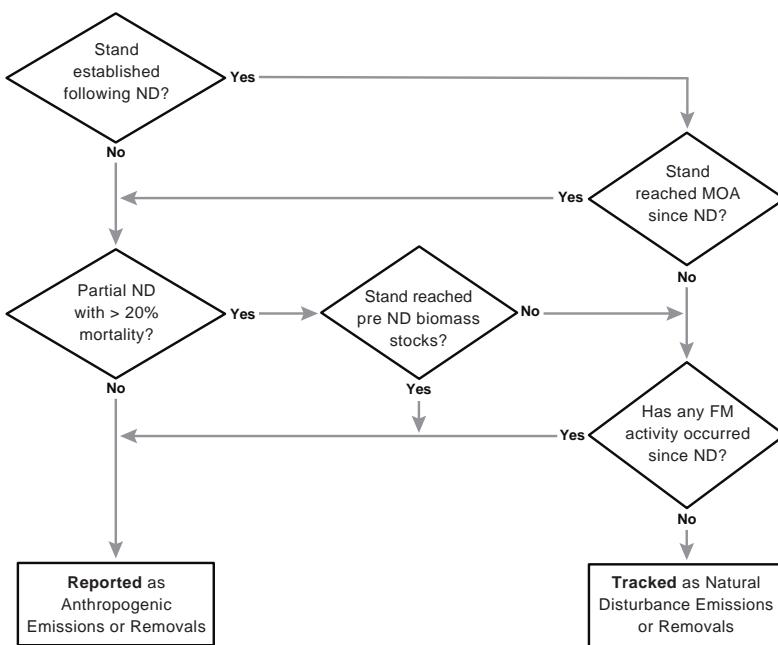
In the current modelling framework, partial natural disturbances occur mainly due to insect infestations. In these cases, above-ground biomass recovery was used to define a recovery period, as the growth trajectory of the stand is only temporarily modified. Stands subject to insect disturbances causing less than or equal to 20% biomass mortality are not deemed to be dominated by natural disturbances; at this low mortality level, disturbances are considered agents that contribute to stand density reductions.

Tracking stands in which emissions and removals are dominated by natural disturbance dynamics is carried out by querying model results based on a decision-tree approach in which key decision points are based on stand origin, type of disturbance (partial or stand replacing) and an annual assessment of post-disturbance status, either commercial maturity threshold or pre-disturbance biomass (Figure A3.5–5).

After exclusion of the non-anthropogenic emissions and removals, the final reported values represent all forest stands in the managed forest land base that have attained commercial maturity or have had their growth trajectory modified by a direct anthropogenic management action in the forest. The area temporarily excluded from reporting in any given year remains relatively constant, within a variation of +2.9/-3.6 million hectares (Mha), as stands undergoing natural disturbance in a given year are removed from reporting and lands that were disturbed historically re-enter reporting. The sum total of each of the stand categories included and excluded is equivalent to the sum of emissions and removals quantified using the methodological approach for reporting total emissions from the managed forest in inventory submissions, prior to implementing the partitioned reporting approach.

Figure A3.5–5 Decision Tree for Differentiating Emissions and Removals from Anthropogenic and Natural Origin

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Notes:

ND = Natural disturbance

MOA = Minimum operable age

FM = Forest management

A3.5.2.5. Forest Conversion

In order to account for long-term residual effects of forest conversion, conversion rates were estimated starting in 1970. The approach for estimating forest areas converted to other land uses before 2010 was based on three main information sources: systematic or representative sampling of remote sensing imagery, records, and expert judgement/opinion. The basic methods were tested in several pilot projects (Leckie, 2006a), and the methodology was implemented across the country. For more recent years, the estimation approach is based on representative sampling and mapping of large forest conversion events from remotely sensed imagery only.

The core method involves remote sensing mapping of forest conversion based on samples from Landsat images dated circa 1975, 1990, 2000, 2008, 2013 and 2018. Change enhancements between two dates of imagery are produced to highlight areas of forest cover change and identify possible forest conversion events (i.e., “candidate events”). The imagery is then interpreted to determine whether the land cover of the candidate event was initially forest (at Time 1) and the actual land-use change at Time 2 (Leckie et al., 2002, 2010b). This forest conversion interpretation process is strongly supported by additional spatial data, including: digitized aerial photographs; snow-covered, leaf-off, winter Landsat imagery; secondary Landsat images from other dates and years; ancillary data, such as maps of road networks, settlements, wetlands, woodland coverage, and mine and gravel pit locations; and specialized databases giving locations of oil and gas pipelines and well pads (Leckie et al., 2006; Dyk et al., 2015). When readily available, detailed forest inventory information is also used.

Change imagery is interpreted and analyzed; each forest conversion event larger than 1 ha is manually delineated. The forest type, maturity and density prior to forest conversion is interpreted,³² and the post-deforestation land use recorded (“post-class”). Confidence ratings on the land use at the initial time and a later time period are used in subsequent quality control and field validation procedures.

Monitoring of forest conversion activity covers all forest areas of Canada and is not limited to the managed forest. The entire forested area of Canada is broadly stratified into regions of expected forest conversion level and dominant cause, which dictate the target sampling intensity. Depending on the expected spatial patterns and rates of forest conversion, sampling approaches range from complete mapping to systematic sampling over the entire analysis unit of interest to a representative selection of sample cells within a systematic grid. For example, in populated areas of southern Quebec, in

³² See Chapter 6 for the definitional parameters of “forest.”

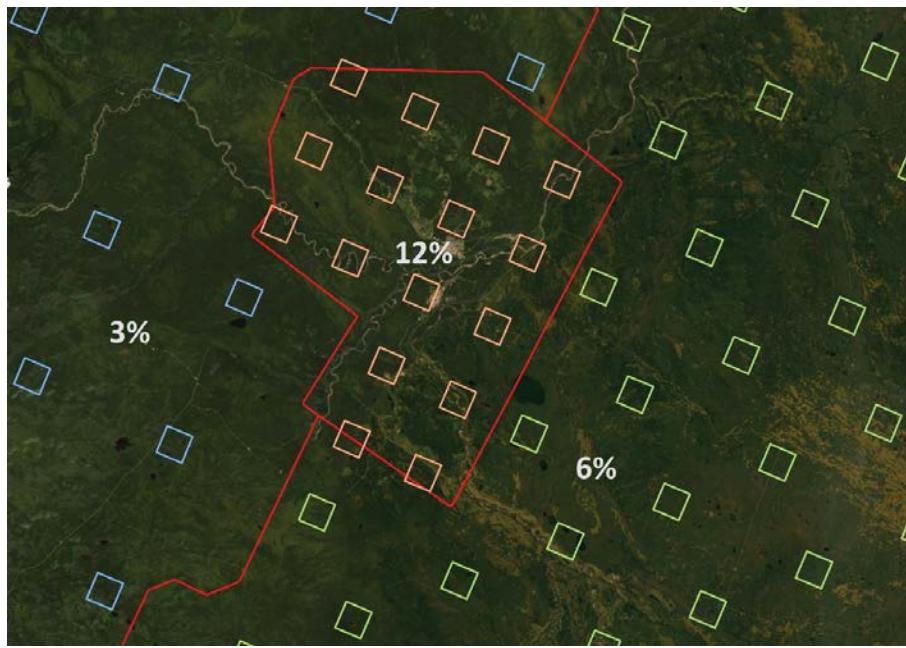
the Prairie fringe and in British Columbia a 12% sampling rate in earlier time periods was generally achieved, with 3.5 km by 3.5 km sample cells at the nodes of a 10 km by 10 km grid (Figure A3.5–6). A lower sampling rate is used in some of the forest activity zones characterized by low population density, where the main economic activities are forestry and other resource extraction. Special cases of known, localized and large forest conversion activities are also identified, such as hydroelectric reservoirs and oil sands development in Alberta. In such cases, the entire areas are handled as single events (“Hot Spot” in Figure A3.5–7), with spatially complete mapping.

In practice, resource constraints limit the size of the remote sensing sample. Wherever possible, a target sampling rate of 12% or 6% was achieved. It is also important to note that different sampling rates may be applied for each time period in an effort to track differing activity rates between time periods. The total areas, either fully mapped or sampled, cover a large portion of the Canadian land base, approximately 346 Mha. This total area was mapped over different time periods, of which over 17 Mha were mapped for 1975–1990, 41 Mha were mapped for 1990–2000, 22 Mha were mapped for 2000–2008, 23 Mha were mapped for 2008–2013 and 15 Mha were mapped for 2013–2018 (Figure A3.5–7). Mapping is updated on a roughly five-year cycle for both the sampling and individual larger events and may be integrated progressively by project for the most recent time period.

Areas of northern Canada were previously unrepresented in the National Deforestation Monitoring System (NDMS) estimate due to expected low activity and as such, zero deforestation had been assumed in this region (Dyk et al., 2015). In order to verify the activity levels in the north, a full coverage deforestation mapping project in the Northwest Territories Taiga Plains (RU50) was initiated based on existing anthropogenic disturbance datasets. RU50 was processed with full area mapping (Figure A3.5–7). Mapping showed that RU50 deforestation represents less than 0.2% of Canada’s annual deforestation rate. The results are reported in this submission (see Chapter 6).

Records were gathered when available. They consist mostly of information on forest roads, power lines, oil and gas infrastructure, and hydroelectric reservoirs (Leckie et al., 2006). The temporal coverage, availability and applicability of these records are assessed to determine the most appropriate information sources (records or imagery). Records data are sometimes used to aid in the validation of estimates made through image interpretation. In particular, early mapping for British Columbia used records data to provide estimates of conversion activity for power lines and oil and gas activity. Remote sensing image interpretation is used to assess the areas of forest converted as a result of hydroelectric development.

Figure A3.5–6 Three Sampling Rates over Satellite Imagery for Forest Conversion Mapping



Note: Background imagery: Area near Fort Nelson, British Columbia (ESRI World Imagery). Denser grid cells at the center represent a 12% sampling density; lighter grid on the right is 6% intensity and sparse grid on the left is 3% intensity.

Expert opinion is only called upon when remote sensing sampling is insufficient and records data are unavailable or of poor quality. Expert judgement is also used to reconcile differences between records and remote sensing information and to resolve large discrepancies in each sequential mapped time period area estimate (i.e., 1975–1990, 1990–2000, 2000–2008, and the most recent time periods are measured on a circa 5 year cycle). In such cases, available expert opinion and data sources are brought together, remote sensing and records data are reviewed, and decisions are made (Leckie, 2006b; Leckie et al., 2010a; Dyk et al., 2015). For most estimates now—and certainly for those with large impact—estimates are derived directly from remote sensing samples.

The activity data are compiled and summarized initially by analysis unit. All conversion events are assembled into a database. A compilation is made to summarize events for detailed post-conversion classes for each RU. This compilation process also involves insertion of records data and expert judgement. In the course of these procedures, each event is compiled to yield a local forest conversion rate (ha year^{-1}) based on the time interval between the images. Since the available imagery was not necessarily dated a specific year, the rates cover different time periods. At the data compilation phase, forest conversion events are assigned a time period, and the corresponding rate of forest conversion is assigned to that period. For example, a 7.0-ha event encountered on imagery from the period 1975–1989 would yield a 0.5 ha year^{-1} rate ($7.0 \text{ ha}/14 \text{ years}$) and then would be assigned to the period 1975–1990. The total area interpreted in an analysis unit for that time period is then used to determine a relative rate of forest conversion (ha year^{-1} per km^2 interpreted) for all events of the same type. Relative rates are scaled up for each analysis unit. Data are finally grouped by end land use (e.g., the change rate for agricultural crop or rural residential) and, in turn, are summarized by broader categories when recompiled by RU.

The remote sensing data are derived using medium-resolution imagery from circa 1975, 1990, 2000, 2008, 2013, 2018 and more recent years as new imagery has become available, whereas records data are annual or summarized over time periods. As explained, the remote sensing core method provides, to date, five distinct average rates of forest conversion for the mapped time periods, but no annual estimates of these rates. The preparation of annual forest conversion rates for 1970 to the current inventory year requires the simultaneous application of two procedures: (i) extrapolation of annual rates prior to 1983 and beyond the mid-point of the latest time period available, and (ii) linear interpolation between the mid-points in the mapped time periods and recent analyses that are completed at the time of submission (Figure A3.5–8). Added to the interpolated data are individual large events for which actual disturbance information is known either from records information or a detailed mapping activity. One example of this would be the case of hydroelectric reservoirs.

Figure A3.5–7 Forest Conversion Strata and Areas Sampled in 2013–2020

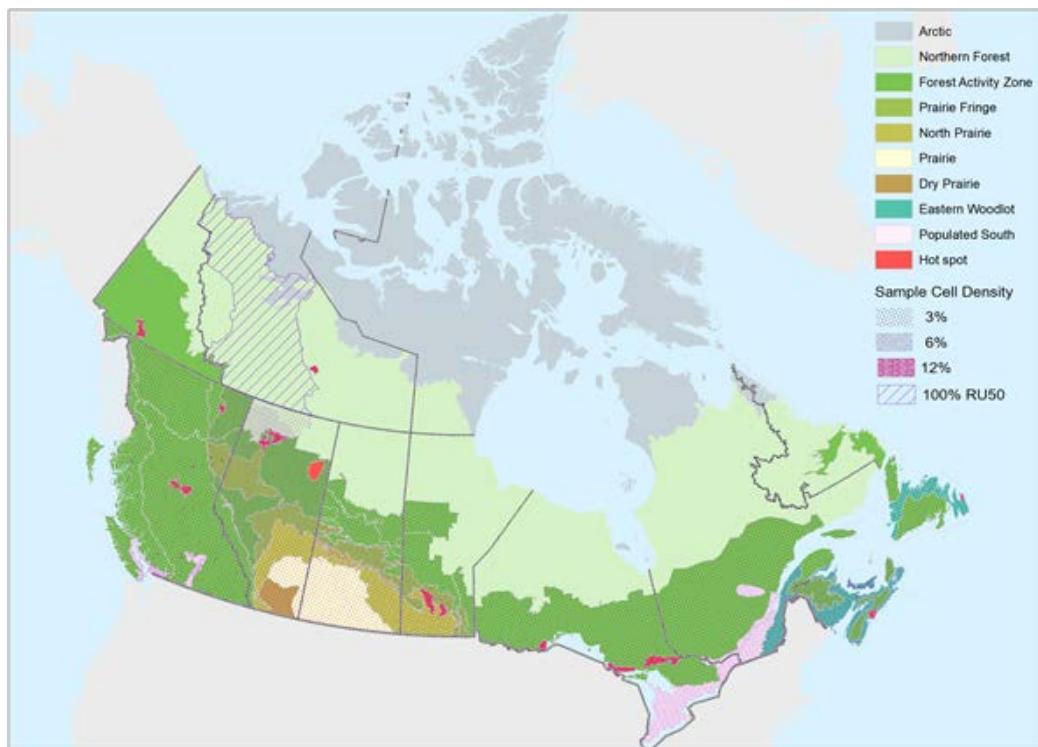
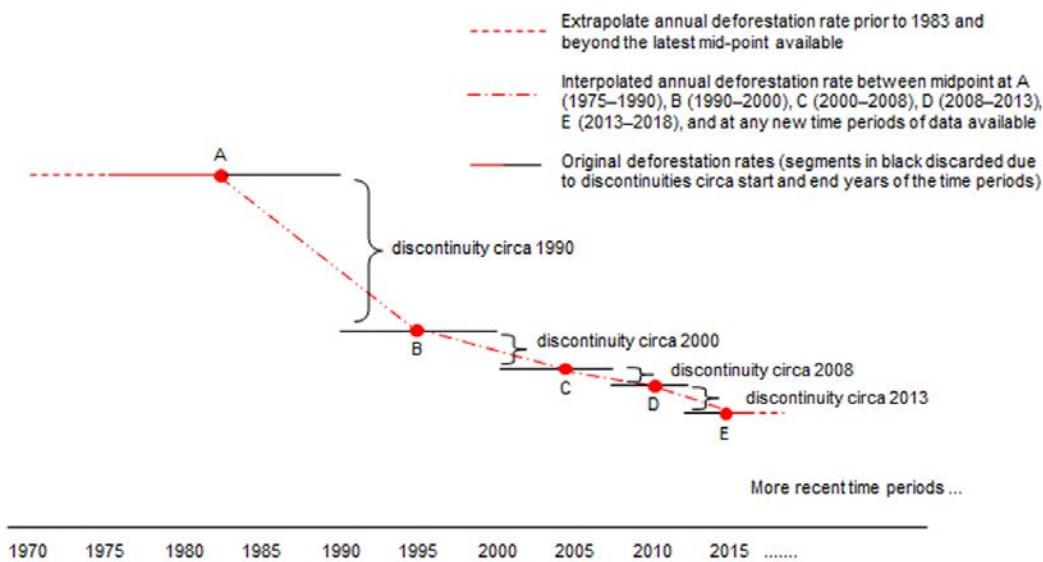


Figure A3.5–8 Procedure for Developing a Consistent Time Series of Forest Conversion Rates

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Quality Assurance / Quality Control of Forest Conversion Data

Great care was taken in understanding the records data, their suitability and their limitations. Documentation of the records data was examined, personnel involved in managing and implementing the data collection and storage were interviewed and, where available, numbers were checked against independent data sources, sampling of high-resolution imagery and the knowledge of experts.

The remote sensing interpretation follows defined procedures (Leckie et al., 2010b; Dyk et al., 2015), although it is conducted by a variety of organizations, including provincial government forestry or geomatics groups, remote sensing or mapping companies, research and development organizations and in-house government staff. The basic image analysis quality control (QC) process includes: internal checks within the mapping agency or company by a senior person; real-time quality assurance (QA) by Canadian Forest Service specialists during interpretation, with feedback provided within days of interpretation of an area; and a final QA and vetting of the interpretation by the Canadian Forest Service. Field validation is conducted on an ongoing basis as resources permit. Each QC point and revision is documented within the geographic information system (GIS) database of conversion events (Dyk et al., 2015).

Records of decision as to data used and expert judgement applied, as well as decisions on the resolution of contradictory data, are documented within the overall processing database (Leckie, 2006b) and updated for each new submission (Dyk et al., 2015). Data sources and limitations are recorded, and remote sensing data and interpretations archived.

Uncertainty of Forest Conversion Data

The development of an uncertainty estimate for forest conversion is a complex and difficult task because of its spatial and temporal variability. Compared to earlier estimates, current estimates benefit from several years of experience and knowledge gained through the development of previous estimates (Leckie, 2011; Dyk et al., 2015). Specific improvements include:

- expanded data sets with additional Earth observation (EO) data, Landsat, Sentinel 2, SPOT-5, aerial photography and high-resolution satellite imagery
- expansion of the sampled area for targeted and other areas
- analysis and validation of records data with high-resolution imagery (for example, co-disturbance of pipelines and access roads)
- extension of the temporal coverage to the most recent time period
- review of the 1970–2004 deforestation time series based on more current spatial analysis
- validation of existing anthropogenic disturbance datasets for northern Canada
- better knowledge resulting from increased experience and expertise gained through QC review and validation activity

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These improvements result in enhanced detection, delineation and determination of event size and cause, as well as a more accurate estimate of timing of conversion events.

Two approaches were considered to estimate uncertainties: an empirical approach and an analytical approach. The resulting estimate is based on consideration of these approaches and provides an estimate of uncertainty associated with activity area estimates. The additional sources of uncertainty related to the forest type being converted, post-conversion land category and event timing are not considered.

The empirical approach is an attempt to estimate an overall uncertainty in the forest conversion area estimate. This approach provides an estimate that considers all of its varied components and their potential interactions.

The empirical estimate was developed by making estimates of extreme low, low, high and extreme high forest conversion rates for each RU and end-use class. These estimates were based on expert knowledge of activity and practices at a regional scale. All of these estimates were then compiled on a national basis. Comparisons between extreme and non-extreme estimates provided some insight into the possible range for which conversion activity could occur. Based on this exercise, an estimate for overall uncertainty for forest conversion was determined to be in the range of $\pm 20\%$ to $\pm 30\%$.

The analytical approach breaks down the uncertainty into subcomponents and then combines them through simple error propagation. The components considered are omission and commission, sampling and boundary delineation errors.

Omission and commission errors are influenced by a number of factors, but in particular are dependent on the date and quality of pre- and post-imagery. Throughout the time series, there is a tendency for omitted events to be smaller in size, whereas commission errors are usually from a misinterpretation rather than an oversight, and thus are less size-dependent. Commission and omission errors tend to offset each other. For the post-2000 time periods, commission errors are likely to be greater than omission errors, particularly because of an insufficient post-disturbance time lapse to confirm that areas are in fact permanently deforested.

Uncertainty associated with boundary delineation errors considers the errors resulting from the displacement of the event boundary from the actual or true boundary of the event. Both underestimation and overestimation of area can result. This source of uncertainty is greatly influenced by the quality and resolution of imagery used in the delineation process; improvements made in resolution and image quality reduce this source of uncertainty.

Estimates of sampling uncertainty take into account the uncertainty associated with the sampling process and the scaling of estimates to large regions (strata/RU). The sampling process is a mixture of wall-to-wall mapping and systematic sampling. In some areas, the sample coverage and design differed between all of the mapping periods. The sample error depends on the amount of activity in each region within each time period sampled. In addition, it is dependent on the conversion event size and spatial distribution (Leckie et al., 2015). Uncertainty due to sampling and scaling activity is therefore regionally variable and, because conversion activity causes may vary by region, the uncertainty is variable.

The results of this analytical approach are consistent with those made based on an empirical approach. Based on these efforts, a conservative estimate is taken, which sets the uncertainty at the higher range of $\pm 30\%$. Further work will help improve the current understanding of the various sources of uncertainty, their interaction and approaches used to combine these components.

The $\pm 30\%$ range is an overall estimate considering all time periods, regions and forest conversion types. Caution should be exercised in applying the 30% range to the cumulative area of forest land converted to another category over the last 20 years, or 10 years for reservoirs (land areas reported in the CRF tables).

A3.5.2.6. Land Converted to Forest Land

Records of land conversion to forest land in Canada were available for 1990–2002 from the Feasibility Assessment of Afforestation for Carbon Sequestration (FAACS) initiative (White and Kurz, 2005). Conversion activities for 1970–1989 and 2003–2008 were estimated based on activity rates observed in the FAACS data. Additional information from the Forest 2020 Plantation Demonstration Assessment was included for 2004 and 2005, and an environmental scan was performed to identify additional sources of information on afforestation rates from 2000 to 2008. Additional afforestation activity data were obtained through a data-sharing agreement with Forests Ontario. A validation exercise on Forests Ontario plantation sites (5 456 spatially-explicit planting records covering 12 466 ha) resulted in 10 390 ha being classified as afforestation events from 2007 to 2016.

For jurisdictions other than Ontario, no afforestation activity data for the post-2008 have been identified. Changes in land use dynamics in Canada since 2008 suggest that it is not reasonable to assume that recent afforestation activity would be similar to the pre-2008 period.

Each event, regardless of date, source, type or location, was converted to an inventory record for the purposes of C modelling. All events were compiled in a single data set of afforestation activity in Canada from 1970 to 2016. For 1990–2016, the area planted was stratified by ecozone, province and tree species. Total area planted by province and ecozone, in conjunction with the proportion of species planted for each province, was used to calculate area planted by species, resulting in estimates of the area converted to forest, by species, for each RU.

Yield curves are not always available for some plantation species or growing conditions (stocking level or site history); those used to estimate growth increments were taken from a variety of sources, most often directly from provincial experts. Growth curves for the Forests Ontario plantation sites were developed using the Forest Vegetation Simulator-Ontario (Woods and Robinson, 2007), which is a variant of the United States Forest Service's simulator adapted for use in Ontario. Where species do not have their own yield curve, they are given the yield curve of another species with similar growth characteristics or the species most likely to have been present in that area. It was assumed that no woody biomass is present on the site prior to afforestation. Changes in soil C stocks are highly uncertain. It was assumed that the ecosystem would generally accumulate soil C at a slow rate; the limited time frame of this analysis and the scale of the activity relative to other land use and land-use change activities suggest that the impact of this uncertainty is minimal.

A3.5.2.7. Estimation of Carbon Stock Changes, Emissions and Removals

At the beginning of each annual time step and when an afforestation or forest conversion event is processed, the CBM-CFS3 first assigns the new land-use classification before the impacts of that event are recorded to ensure that the impacts of land-use change (conversion to forests and conversion of forests) are reported in the new land category. The selection of forest stands affected by land-use change and non-land-use change disturbances is based on eligibility rules (Kurz et al., 2009).

Once the model has computed the immediate effect of disturbances on all forest stands, it simulates forest growth, litterfall and turnover, and decomposition as well as the associated C transfers (annual processes) for all records (managed forest, land converted to forest and land converted from forest), including both stocked and non-stocked stands. The model output consists of C stock changes, fluxes and immediate emissions from burning from which the net GHG balance of managed forests can be calculated. Component fluxes include growth, immediate emissions due to disturbances (C stock changes, C losses to the atmosphere and to forest products), and decay of both DOM and soil organic matter, including on stands affected by disturbances. During this stage, inventory records that have been in a “Land Converted to” category for 20 years (10 years for land converted to reservoirs) are converted into the “Land Remaining” category, and the simulation of C dynamics—usually decay—continues in this new category.

The same data outputs are available on converted forest lands (except tree growth), but are reported in the new land category—e.g., the Forest Land Converted to Cropland (CRF Table 4.B subcategory 2.1), Land Converted to Wetlands (CRF Table 4.D subcategories 2.1 and 2.2.1) and Forest Land Converted to Settlements (CRF Table 4.E subcategory 2.1) categories. Exceptions consist of estimates of soil organic matter emissions on forest land converted to cropland and peat extraction fields, which are developed separately; methods are described in sections A3.5.4.3 and A3.5.6.1. Likewise, estimation methods for emissions (as opposed to C stock changes) from forest land converted to flooded lands are described in section A3.5.6.2 and for emissions from the use and disposal of forest products are described in section A3.5.3.

A3.5.2.8. Uncertainties

Good practice recommends the use of numerical methods for assessing uncertainties within complex modelling frameworks with multiple interactions between data and parameters. These methods are data intensive and computational requirements can quickly become a limiting factor. Not all model parameters or input data have equal influence on model outputs. Careful consideration must therefore be given to balance available computing capacity and the inclusion in the uncertainty assessment of input data, parameters and other functions with a large influence on model outputs.

The general approach to uncertainty assessment emphasizes model inputs and parameters as the main sources of uncertainty. The specific uncertainty sources are forest inventory data, influential model parameters and the initialization of soil and DOM C stocks prior to model runs. Additional randomization steps are also fed into the development of confidence intervals, by randomly selecting 10 000 bootstrap samples of the output from 100 national-scale Monte Carlo runs (Metsaranta et al., 2017). Not all sources of uncertainty have been captured. Importantly, the analysis did not consider the impact of processes that are currently not simulated (Kurz et al., 2013); hence, the results should not be used to assess potential bias (or accuracy) of estimates. The following paragraphs provide details on the characterization of uncertainty sources.

The forest inventory data used in model simulations are developed for planning and operational purposes. Methods, standards, definitions and quality differ by jurisdiction, depending on their objectives. Although documentation on the different inventory techniques and procedures used across the country is usually available, it seldom contains any quantitative assessment of uncertainty. While it is currently impossible to quantify uncertainties about, for example, managed forest

Table A3.5–4 Uncertainty Ranges for Harvested Carbon, by Canadian Province and Territory

Province or Territory	Minimum Multiplier	Maximum Multiplier
NL	0.96	1.04
PE	0.88	1.12
NS	0.88	1.12
NB	0.92	1.08
QC	0.86	1.14
ON	0.92	1.08
MB	0.86	1.14
SK	0.92	1.08
AB	0.90	1.10
BC	0.92	1.08
YT	0.84	1.16
NT	0.74	1.26

Note:
Source = Metsaranta et al. (2014)

areas, the influence of this uncertainty source can be indirectly built into the uncertainty about the biomass increment simulated by the model. For the purpose of this assessment, a 50% uncertainty about biomass increment is assumed. In addition to managed forest areas, it incorporates uncertainties about the age-class distribution, yield curves and allometric equations that enter the estimation.

The areas of managed forests affected annually by both natural and anthropogenic disturbances have a large influence on forest C dynamics as a whole. Disturbances affect emissions and removals of C in the short term as well as in the long term through residual decay and age-class distribution. Uncertainties of 10% and 25% are assumed on the areas of managed forests subject annually to wildfires and insect infestations, respectively. The limited total forestry drainage area suggests that the impact of the uncertainty associated with this activity is minimal.

The uncertainties about the C removed in harvested material are regionally specific and incorporate error ranges in harvested volume ($\pm 1\%$) and standard deviations about roundwood-specific gravity and the bark adjustment factor (Table A3.5–4). No error was assumed for the C proportion of biomass. The annual coefficient of variation was multiplied by 2 to approximate a normal distribution with a triangular one.

The assessment also provides uncertainties about emissions due to forest conversion that are subsequently used in Tier 1 uncertainty reporting for national estimates in conjunction with the 30% uncertainty for areas converted annually equally used in this analysis. The “Forest Conversion” section of this annex describes the derivation of this value (see A3.5.2.5).

Soil and DOM pools contain a considerable amount of C. Previous work has shown that the initial DOM C stocks, at the beginning of a complete run, are sensitive to historical disturbance rates. In this assessment, initial C stocks in the soil and DOM pools were allowed to vary by modifying the historical (pre-1990) fire return intervals. Even though the rates of soil organic matter decay modelled by the annual processes are very low, they do, by virtue of the pool size and forest areas, strongly influence emissions from annual processes. A sensitivity analysis of C emissions from the DOM and soil pools revealed that the most influential model parameters included decay rates for soil organic matter and the decay and release to the atmosphere of C from very-fast cycling pools, such as dead fine roots and litter (White et al., 2008).

For the purpose of this analysis, 28 model parameters are allowed to vary in the Monte Carlo runs:

- base decay rates for DOM pools (11 parameters)
- proportion of decayed material that is oxidized, versus that which is transferred to another DOM pool (5 parameters)
- turnover rates for biomass pools (12 parameters)

In the absence of evidence to support more complex functions, all input probability distribution functions for biomass increments, activity data on human and natural disturbances and decay parameters are triangular. A gamma probability distribution function is used for fire intervals (Metsaranta et al., 2014).

It is thought that significant uncertainty in the modelling framework may result from the random selection of forest stands subject to fire and deforestation disturbances (Kurz et al., 2008b), which interacts with the uncertainty about forest inventory data. The random effect of stand selection algorithms is included in the analysis by allowing different seed values to initiate the random selection algorithms.

It is important to note the interactions between input data and parameters. For example, the uncertainty about the age of a forest stand (or age-class structure of a forest landscape) may affect the simulated stand (or landscape) productivity, depending on the yield curves and the particular locations of a given age category along those curves. Emissions due to disturbances—including the conversion of forests to other land categories—are driven not only by the areas affected, but also by the pre-conversion standing C stocks, the parameters of the disturbance matrices that reallocate C among pools or “release” it to the atmosphere and the post-conversion decay rates. Hence, uncertainties about estimates cannot be obtained from a simple combination of “activity data” and “emission factor” uncertainties.

Uncertainty estimates are developed for both reported emissions and removals representing anthropogenic drivers and non-reported emissions and removals due to natural disturbances. In years where there are no substantial changes, no comprehensive uncertainty analysis using Monte Carlo simulation is performed. Instead, confidence intervals for each category for the current year of submission are statistically extrapolated for both forest and HWP estimates. These extrapolations use the results of the previous submission, where numerical estimates of uncertainty were derived using Monte Carlo simulations as explained above and further described in Metsaranta et al. (2017, 2020). Total uncertainty estimates are allocated to the reported and non-reported categories using the same categorization procedures used to estimate reported and excluded values (see section A3.5.2.4).

Additional considerations may be warranted to identify the direct human-induced effects, and their uncertainties, on forest C dynamics. Improvements are expected to occur over coming years, due to better knowledge, refined procedures, improved computer software implementations and access to more computing capacity.

A3.5.3. Harvested Wood Products

The LULUCF sector of the inventory includes an estimate of the CO₂ emissions associated with the use and disposal of HWP manufactured from wood resulting from forest harvest, forest conversion and firewood collection activities in Canada and consumed either in Canada or elsewhere in the world, in accordance with the general framework of the Simple Decay Approach, as described in the Annex to Volume 4, Chapter 12, of the 2006 IPCC Guidelines (IPCC, 2006). The approach is similar to the Production Approach, but differs from it in that the HWP pool is treated as a C transfer related to wood harvest and hence does not assume instant oxidation of wood in the year of harvest. The approach tracks the fate of C in all woody biomass harvested domestically and taken off-site. Emissions of CO₂ from HWP use and disposal are estimated and reported by the LULUCF sector, while CH₄ and N₂O emissions from HWP combustion or domestic decomposition are estimated and reported by the Energy and Waste sectors.

General Approach and Methods

A country-specific model, called the National Forest Carbon Monitoring, Accounting and Reporting System for Harvested Wood Products (NFCMARS-HWP), was developed to estimate and report on the fate of C harvested in Canada’s forests and other wooded lands.

Model Inputs and Data Sources

Input to the model includes the annual mass of C transferred to forest products that result from conventional forest harvesting in forests, residential firewood collection in forest and other wooded lands and from forest conversion activities since 1990. It is spatially distributed by RU (see section A3.5.1), as calculated by the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, see section A3.5.2.1), thus ensuring there are no gains or losses as C flows from wood producing lands to products.

Data on the annual volume of residential firewood and industrial wood waste used for bioenergy are provided by the Energy sector. In the case of residential firewood, the consumption data were collected through a survey of residential wood use for the years 1997, 2003, 2007, 2015, 2017 and 2019 (Statistics Canada, 1997, 2003, 2007, 2015, 2017, 2019). Pellet and manufactured log consumption data were collected for the years 1996, 2006, 2012, 2017 and 2019 (Canadian Facts, 1997; TNS, 2006, 2012; Statistics Canada, 2017, 2019). These data were collected only for the provinces (i.e. not for the territories) and grouped into major appliance-type categories that include: advanced and conventional fireplaces and fireplace inserts, wood stoves, wood furnaces, pellet stoves, hydronic heaters, water heaters and other equipment. The 2017 and 2019 surveys also collected data on the type of wood used for firewood that was spatially aggregated by RU (Trégaro, 2020). As a result, species-dependant wood densities could be applied (Blondel and Tracey, 2018) which were maintained constant throughout the time series. The pellet and manufactured log consumption data were collected on a mass basis. These data were interpolated and extrapolated to other years using the number of heating degree days in each province in relation to the survey years. Data on firewood consumption for the territories come from fuelwood and firewood harvest statistics provided by the National Forestry Database³³ and data on industrial consumption of fuelwood (biomass and spent pulp liquors) for energy production come from the annual *Report on Energy Supply and Demand in Canada* (RESD). See section A3.1.4.1.4 for more details.

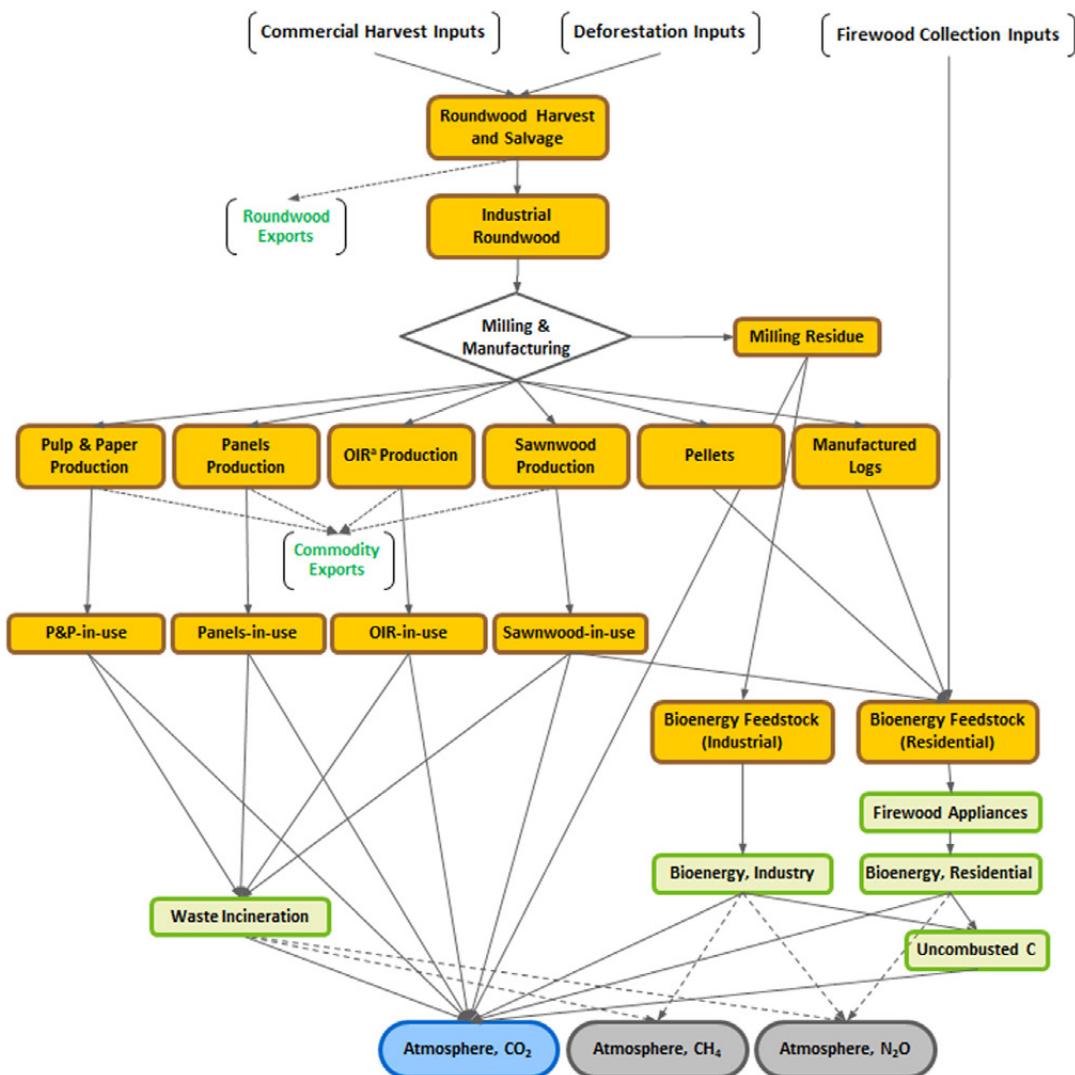
³³ National Forestry Database, available online at: <http://nfdp.ccfm.org/en/data/harvest.php>

For historical harvest, the C input comes from commodity production data from Statistics Canada at a national level of spatial resolution and covering the 1941–1989 period. For the 1900–1940 period, the C inputs are backcast based on historical production data by extrapolating information from the 1941–1989 period, while the consumed and exported magnitudes are calculated using average proportions from statistics in the five-year period from 1961 to 1965.

Model Flow and Parameters

The model uses a conceptual flow network describing the movement and transformation of harvested wood (see Figure A3.5–9). The model takes the C inputs and, in annual time steps, exports some of the harvested roundwood, converts all harvested wood into commodities (sawnwood and other-industrial roundwood, wood-based panels, pulp and paper, pellets and manufactured logs used for bioenergy, and residuals referred to as “milling residue”), exports some of the commodities produced, and keeps track of the additions to and retirements from HWP in-use and used for bioenergy. The complete model consists of 15 such networks—one for each province and territory (except Nunavut), plus one each for the United States and Japan, and one that combines all other importers of Canadian wood products. The on-site decay of harvest residues continues to be captured in C stock changes in the DOM pool of the Forest Land category.

Figure A3.5–9 A Simplified Schematic of Carbon Flows in Harvested Wood Products



Recent statistics available in the FAO databases of Forestry Production and Trade³⁴ and Forestry Trade Flows³⁵ were used to determine the proportion of Canadian roundwood and commodity production exported to three main destinations. For example, according to current statistics from the FAO, in any given year, around 98% of industrial roundwood from domestic harvest remains in Canada for further transformation, of which about 70% is converted to sawnwood, wood-based panels, other industrial roundwood or pulp and paper products. Likewise, over the entire time series, around 33% of sawnwood, between 19% and 65% of wood-based panels and less than 13% of pulp and paper are used domestically. The proportion of HWP transferred out of the in-use pool is determined through the application of Equation 12.1 from Volume 4, Chapter 12 of the IPCC 2006 Guidelines (IPCC, 2006). Upon being retired from the in-use pool, all C is assumed to be instantly oxidized. Emissions from residential firewood use and industrial processes flowing from milling residue (e.g., industrial bioenergy) have been represented separately to prevent any potential overlap with estimates reported by the Energy sector.

Manufacturing efficiencies determine the proportion of industrial roundwood biomass converted into commodities—the unused fraction being milling residue. These proportions are calculated using a mass-balance approach that reconciles domestic harvest with FAO data on commodity production and trade. Manufacturing efficiencies are calculated annually for each commodity type: for Canada, the United States and Japan separately; and jointly for all other export destinations. Default bark expansion factors and wood C content were used for all countries (Table A3.5–5). Default parameters were used to convert product volume to units of C for countries other than Canada and the United States and where country-specific parameters are not available for Canada or the United States (Table A3.5–6). Canada-specific wood density values were used for domestic roundwood, sawnwood, other industrial roundwood and panels, and default values were used for domestic pulp and paper market. Country-specific values were used for all domestic quantities for the United States. Default values were used for domestic and imported quantities for Japan and elsewhere. It is assumed that all wood fibre feedstock produced in a given year is processed by the forest products manufacturing sector in the same year.

All wood transferred from the forest to the HWP pool is included in the HWP model, but some of the products associated with portions of the wood, such as wood chips and pellets, are not explicitly identified in the data. Contrary to other HWP wood, chips and pellets are estimated from firewood consumption surveys. Wood used for bioenergy, such as pellets and chips, is assumed to be sourced from the “milling residue” output category in the HWP model (see Figure A3.5–9). This C is quantified and allocated to bioenergy but is undifferentiated from other residual waste, all of which is assumed to be oxidized on disposal. The export of wood chips/pellets is currently not considered in the model.

The model starts the pool in 1900 and applies product in-use half-life parameters to wood product types based on geographic location. Half-life parameters are sourced directly from Table 3a.1.3 of IPCC (2003) or derived from that table using production-weighted averages to fit the wood product categories of the NFCMARS-HWP (Table A3.5–7).

Table A3.5–5 Default Parameter Values Used in HWP Analysis

Description	Units	Value
Bark expansion factor, Softwoods	dimensionless	1.11 ^a
Bark expansion factor, Hardwoods	dimensionless	1.15 ^a
Bark expansion factor, Mixedwoods	dimensionless	1.13 ^a
C content of wood	tonnes C od tonne ^{-1, c}	0.5 ^b

Note:

- a. IPCC (2006) (Vol. 4, Table 12.5)
- b. IPCC (2006) (Vol. 4, Table 12.4)
- c. Tonnes carbon per oven dry tonne (od tonne) of wood material.

34 FAOSTAT Forestry Production and Trade, available online at: <http://www.fao.org/faostat/en/#data/FO>

35 FAOSTAT Forestry Trade Flows, available online at: <http://www.fao.org/faostat/en/#data/FT>

Table A3.5–6 Wood Densities of Commodities

Country/Countries	Description	Units	Value
Canada	Species-weighted average density, Roundwood	od tonne m ⁻³	0.386 ^a
Canada	Species-weighted average density, Sawnwood	od tonne m ⁻³	0.481 ^a
Canada	Species-weighted average density, Other industrial roundwood	od tonne m ⁻³	0.583 ^a
Canada	Species-weighted average density, Panels	od tonne m ⁻³	0.643 ^b
Canada	Species-weighted average density, Bioenergy	od tonne m ⁻³	0.523 ^c
U.S.	Coniferous (C) roundwood	od tonne green m ⁻³	0.455 ^d
U.S.	Nonconiferous (NC) roundwood	od tonne green m ⁻³	0.527 ^d
U.S.	C+NC roundwood	od tonne green m ⁻³	0.465 ^d
U.S.	Hardwood (HW) plywood & veneer	tonnes C m ⁻³	0.28 ^e
U.S.	Softwood (SW) lumber	tonnes C m ⁻³	0.22 ^e
U.S.	HW lumber	tonnes C m ⁻³	0.26 ^e
U.S.	Particle board	tonnes C m ⁻³	0.29 ^e
U.S.	Hardboard	tonnes C m ⁻³	0.42 ^e
U.S.	Medium density fibreboard	tonnes C m ⁻³	0.32 ^e
U.S.	Fibreboard, compressed	tonnes C m ⁻³	0.37 ^a
U.S.	Pulp, paper & board	tonnes C ad tonne ⁻¹	0.42 ^e
U.S.	Insulating board	tonnes C m ⁻³	0.45 ^e
All	Sawnwood – C	od tonne m ⁻³	0.45 ^f
All	Sawnwood – NC	od tonne m ⁻³	0.45 ^f
All	Panels, structural	od tonne m ⁻³	0.628 ^f
All	Panels, non-structural	od tonne m ⁻³	0.628 ^f
All	Paper	od tonne ad tonne ⁻¹	0.9 ^f
All	Wood pulp	od tonne ad tonne ⁻¹	0.9 ^f

Notes:

od tonne = Oven dry tonne of wood material

ad tonne = Air dry tonne of product

a. Country-specific values derived from internal analysis of Canada's forest management levels carried out in 2011–2012

b. Derived from Briggs D (1994)

c. Average of the values for roundwood, sawnwood, other industrial roundwood and panels

d. FAO (2010)

e. Skog (2008)

f. IPCC (2006) (Vol. 4, Table 12.4)

Table A3.5–7 Half-Life Parameters (Years) of Harvested Wood Products In-Use

Country/Countries	Description ^a	Value
Canada	Sawnwood	35 ^b
Canada	Wood panels	25 ^c
Canada	Pulp and paper	2 ^b
Canada	Other industrial roundwood	35 ^b
U.S.	Sawnwood	40 ^b
U.S.	Wood panels	27.04 ^c
U.S.	Pulp and paper	3.25 ^c
U.S.	Other industrial roundwood	40 ^b
Rest of world	Sawnwood	35 ^b
Rest of world	Wood panels	25 ^c
Rest of world	Pulp and paper	2 ^b
Rest of world	Other industrial roundwood	35 ^b

Note:

a. Firewood and mill residue assumed to be burned for the former, or disposed of for the latter, in the year of harvest.

b. IPCC (2003) (Appendix 3a.1, Table 3a.1.3)

c. Derived from IPCC (2003) (Appendix 3a.1, Table 3a.1.3)

Biomass Combustion

Biomass emissions as reported in the Energy sector are grouped into three main sources: (i) residential firewood, (ii) industrial wood wastes (including spent pulp liquors), and (iii) fuel ethanol/biodiesel (assumed not to come from wood waste or pulp liquors).

Residential firewood combustion produces CO₂, CH₄, N₂O and some remaining unaccounted C likely found in VOCs, unburned hydrocarbons and charcoal assumed to be instantly oxidized, in amounts that are dependent on the combustion technology used. Emissions are derived by multiplying the amount of wood burned in each appliance type by the emission factor for that appliance type. The relevant emission factors are given in Table A6.6–1 expressed as grams of gas emitted per kilogram of fuel combusted, which for the purpose of the model have been converted to tonnes of C emitted as gas per tonne C in fuel.

Emissions from industrial use of wood-based energy (managed as “milling residue” in the model) are assumed to result from the combustion of wood wastes (i.e., hog fuel) and spent pulping liquors by the pulp and paper manufacturing sector. As with residential bioenergy use, emissions from industrial use of biomass energy are derived by multiplying the amount of fuel consumed by the emission factor for that fuel type. The emission factors for both industrial wood waste and spent pulp liquors are also given in Table A6.6–1. Note that the emission factors for industrial wood waste and spent pulp liquors are expressed as grams of gas emitted per kg of fuel consumed, assuming 0% moisture content of the fuel.

The processing of residential firewood data ensures consistency with the Energy sector and that the impacts of this type of harvest on the forest and other wooded ecosystems are represented in land emission modelling at the finest possible spatial resolution (Trégaro, 2020). All biomass C inputs to the firewood pool are based on the annual volumes provided by the Energy sector. Specifically, annual quantities of residential bioenergy consumption (in tonnes C) are calculated for each RU, for each of seven (7) allocation categories: (i) softwood collected from forest, (ii) hardwood collected from forest, (iii) mixedwood collected from forest, (iv) woody biomass collected from croplands, (v) firewood collected from urban trees in settlement lands, (vi) pellets, and (vii) manufactured logs, representing the targets of firewood collection to be implemented in the models (Trégaro, 2020; Trégaro and Blondel, 2019; Hafer et al., 2020). Targets for the first three categories in the list were implemented in the CBM-CFS3 simulations (see A3.5.2.3), while targets for the last four categories were implemented in the HWP model. Impacts of firewood collection on Cropland and Settlements land-use categories were estimated (see sections A3.5.4.1 and A3.5.7.1 for more details).

Uncertainty

Uncertainty estimates associated with this category are mainly based on the uncertainty of the C inputs, namely (i) the C estimated as forest products from forest harvest and forest conversion in the CBM-CFS3 model, (ii) the volume of residential firewood provided by the Energy sector, and (iii) available statistics of pre-1990 commodity production.

The implementation of the uncertainty analysis (Metsaranta et al., 2020) divides the uncertainty into three categories: (i) uncertainties in assumptions and approaches (e.g., the assumption that disposal of HWP follows the exponential decay pattern), (ii) uncertainties in factors or parameters that are not derived from activity data (e.g., half-lives of commodity-in-use pools and landfill pools), and (iii) uncertainties in input and allocation parameters that refer to C mass inputs (e.g., roundwood harvest) and partitioning parameters derived from activity data.

A sensitivity analysis was used to filter out parameters whose variations are unlikely to cause significant changes to the emission results prior to the Monte Carlo analysis. Uncertainty distributions and ranges were based on literature where possible and where no distributions were available were based on expert judgement.

Additional parameters were added to the Monte Carlo analysis including uncertain distributions for historical inputs (pre-1990 harvest), contemporary inputs (harvest since 1990) and five allocation parameters related to bioenergy that were added to the HWP model structure. The historical inputs are directly allocated to commodity-in-use pools and are varied using a multiplier which is assigned a uniform distribution with a range between 0.75 and 1.25. Contemporary inputs are acquired from the outputs of the CBM-CFS3 model, which correspond to a range of C mass. These outputs are used as inputs for the uncertainty analysis for HWP. Three sets of pools with their corresponding events and parameters were also added to the analysis: pellets, manufactured logs and bioenergy (residential and industrial). The sample size (n) for the Monte-Carlo runs was 100.

As already noted in A3.5.2.8, in years where there are no substantial changes, no comprehensive uncertainty analysis is performed and, instead, confidence intervals for each category for the current year of submission are statistically extrapolated using the results of the previous submission.

A3.5.4. Cropland

The methodologies described in this section apply to C stock changes in mineral soils subject to cropland management and to the conversion of land in the Forest Land and Grassland categories to the Cropland category, CO₂ emissions from the cultivation of histosols, changes in the biomass of woody perennial crops, and N₂O emissions from soil disturbance upon conversion to cropland. The estimation methodologies for C stock changes and GHG emissions from the biomass and DOM pools upon conversion of forest land to cropland are provided in section A3.5.2.7.

A3.5.4.1. Cropland Remaining Cropland

A detailed description of the methodologies used for tillage practice, perennial/annual crop conversion, and forest land and grassland conversion to cropland can be found in McConkey et al. (2007a).

Change in Carbon Stocks in Mineral Soils

Changing Management Practices

The amount of organic C retained in soil represents the balance between the rates of input from crop residues and losses through soil organic carbon (SOC) decomposition. How the soil is managed determines whether the amount of SOC stored in a soil is increasing or decreasing. The development of the CO₂ estimate methodology is based on the premise that, on long-existing cropland, changes in soil C stocks over time occur following changes in soil management that influence the rates of either C additions to, or C losses from, the soil. If no change in management practices occurs, the C stocks are assumed to be at equilibrium, and hence the change in C stocks is deemed to be zero.

A number of management practices are generally known to increase SOC in cultivated cropland, such as reduction in tillage intensity, intensification of cropping systems, adoption of yield-promoting practices and re-establishment of perennial vegetation (Janzen et al., 1997; Bruce et al., 1999). Adoption of reduced tillage (RT) or no-till (NT) can result in significant accumulation of SOC compared with intensive tillage (IT) (Campbell et al., 1995, 1996a, 1996b; Janzen et al., 1998; McConkey et al., 2003). Many cropping systems can be intensified by increasing the duration of photosynthetic activity through a greater use of perennial forage (Biederbeck et al., 1984; Bremer et al., 1994; Campbell et al., 1998). Switching from conservative to conventional tillage or from intensive to extensive cropping systems will generally reduce C input and increase organic matter decomposition, thereby reducing SOC.

VandenBygaart et al. (2003) compiled published data from long-term studies in Canada to assess the effect of agricultural management practices on SOC. More recent analyses (Fan et al., 2017; Liang et al., 2020a,b; Liang et al., 2021) have been carried out that are guiding new methodological developments. The original compendium and these new studies, as well as the availability of activity data from the *Census of Agriculture*, provide the basis for identifying key management practices and management changes used to estimate changes in soil C stocks. Emissions and removals of CO₂ from mineral soils are estimated for the following land management changes (LMCs):

1. Change in mixture of crop type
 - a) Increase in perennial crops
 - b) Increase in annual crops
2. Change in tillage practices
 - a) IT to RT
 - b) IT to NT
 - c) RT to IT
 - d) RT to NT
 - e) NT to IT
 - f) NT to RT
3. Change in crop productivity/crop residue C input
4. Manure application

Where nutrients are strongly limiting, proper fertilization can increase SOC. In such conditions, however, fertilizer or other nutrient-enhancing practices are generally applied. Irrigation in semi-arid areas can affect SOC, but the impact is unclear and the area of irrigated land has been relatively constant in Canada. Therefore, it is assumed that the selected LMCs represent the most important and consistent influences on SOC in mineral soils.

Area-Based Carbon Stock Change Factor

To estimate C emissions or removals, an SOC stock change factor specific to each combination of SLC polygon and management change is multiplied by the area of change. The factor is the average rate of SOC change per year and per unit of area of LMC.

Equation A3.5–1

$$\Delta C = F \times A$$

ΔC	=	change in SOC stock for inventory year, Mg C
F	=	average annual change in SOC subject to LMC, or C factor, Mg C ha ⁻¹ yr ⁻¹
A	=	LMC area, ha

Areas of LMC, such as changes in tillage and crop type, are obtained from the *Census of Agriculture*. Census data provide information on the net change in area over five-year census periods. In practice, land probably both enters and leaves a land management practice, and combinations of management changes occur. However, because only net change data are available, two assumptions are made: additivity and reversibility of SOC factors. Reversibility assumes that the factor associated with an LMC from A to B is the opposite of that associated with the LMC from B to A. Additivity assumes that the C changes from each individual LMC occurring on the same piece of land are independent and therefore additive. This assumption is supported by the findings of McConkey et al. (2003), who reported that the impact of tillage and crop rotations on SOC is additive.

There is a relatively large set of Canadian observations of long-term changes in SOC for LMCs such as adoption of NT (VandenBygaart et al., 2003; Campbell et al., 2005; Liang et al., 2020). However, even this large data set does not cover the whole geographical extent of Canadian agriculture. In addition, there are difficulties in comparing measurements among research sites, in determining the duration of an effect, in estimating full uncertainty from a range of initial soil conditions and in determining the variability of soil C stocks without management change.

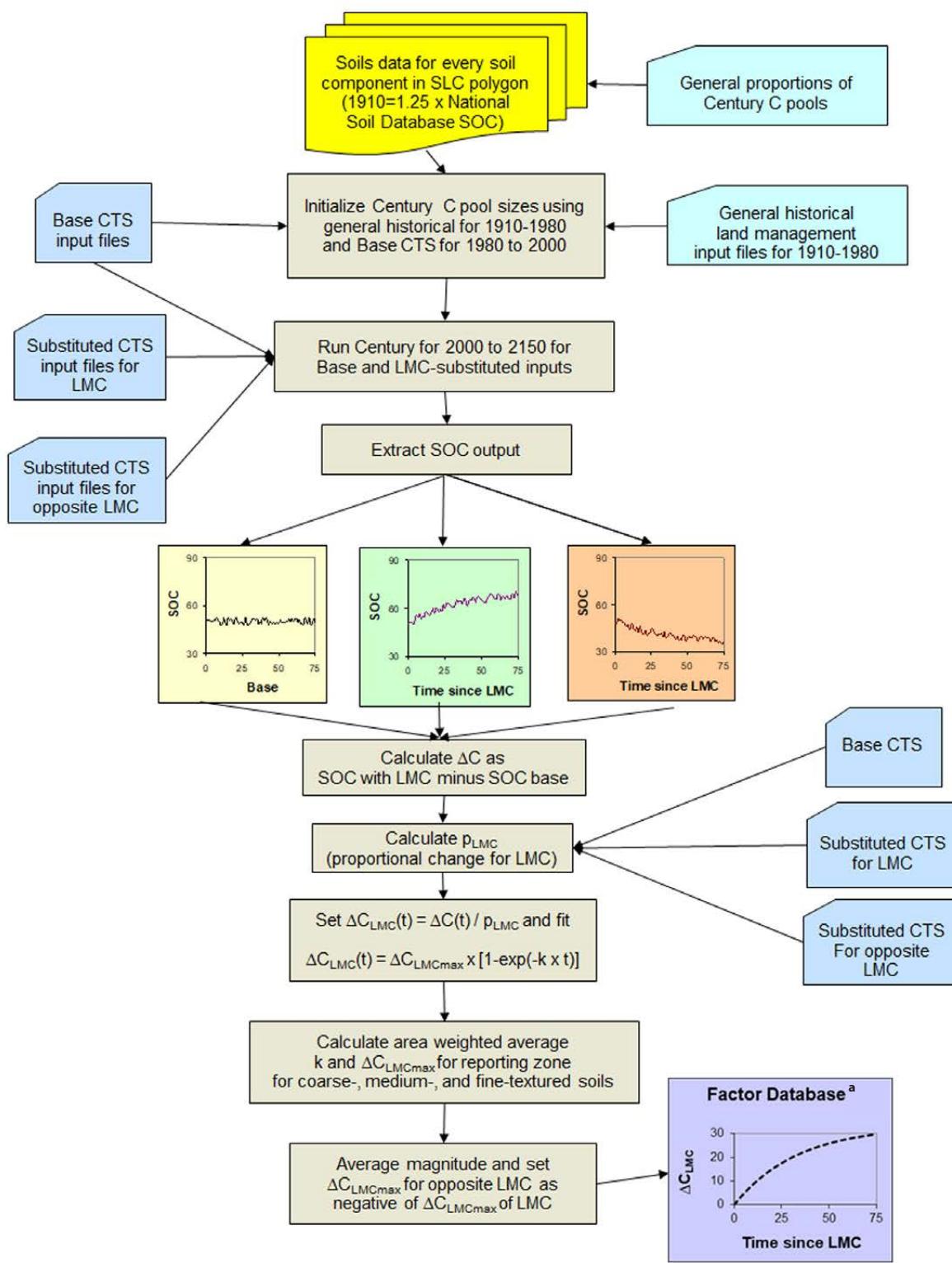
Because of these limitations, a well-calibrated and validated model of SOC dynamics, the Century model (Parton et al., 1987, 1988), was used to derive individual SOC factors for changes between NT and IT, RT and IT, RT and NT, and annual and perennial crops. The Century model had been widely used to simulate SOC change for Canadian conditions (Voroney and Angers, 1995; Liang et al., 1996; Monreal et al., 1997; Campbell et al., 2000, 2005; Pennock and Frick, 2001; Carter et al., 2003; Bolinder, 2004).

Smith et al. (1997, 2000, 2001) developed an approach using the Century model to estimate SOC change on agricultural land in Canada. To estimate C change, it was necessary to develop a generalized description of land use and management from 1910 onwards on cropland for a sample of soil types and climates across Canada. These scenarios were generated from a mixture of expert knowledge and agricultural statistics of land management, including crop types, fallow and fertilizer application (Smith et al., 1997, 2000). These have been used for the first comprehensive assessments of SOC change on agricultural land within a broader assessment of soil health (McCrae et al., 2000).

The starting points for developing C factors for tillage and crop mixtures were the SOC values in the SLC polygon attribute database (CanSIS) (Figure A3.5–10 and Figure A3.5–11). These SOC values were derived from measurements made for soil surveys and land resource studies (Tarnocai, 1997) and were assumed to represent average SOC on cropland in 1985. Initial SOC in 1910 was estimated as 1.25 times the SOC in the SLC polygon. Changes in SOC factors were estimated using the difference in SOC stocks over time between simulation of a generalized land use and management scenario with and without the LMC of interest (Smith et al., 2001).

To develop the area-based factors, a 10-year crop-and-tillage system (CTS) was developed for each analysis unit and census year, using data from the *Census of Agriculture*. The CTS focused on six crops or crop types (grain, oilseeds, pulses, alfalfa, root crops and perennial crops) and three tillage practices (IT, RT and NT). Essentially, each CTS represents a mix of crops and tillage practices in space as a mix of crops and tillage practices in time. Under this scheme, a polygon with 20% of cropland area in grain and 20% of cropland area in NT, for example, has 2 of 10 years in grain and 2 of 10 years in NT. Temporal sequences of crop and tillage practices are developed from expert-defined rule-sets, such as “summerfallow never follows summerfallow” and “corn typically follows soybeans.” The construction allows a base CTS and substitutions of LMCs in the CTS to be readily input to the Century model.

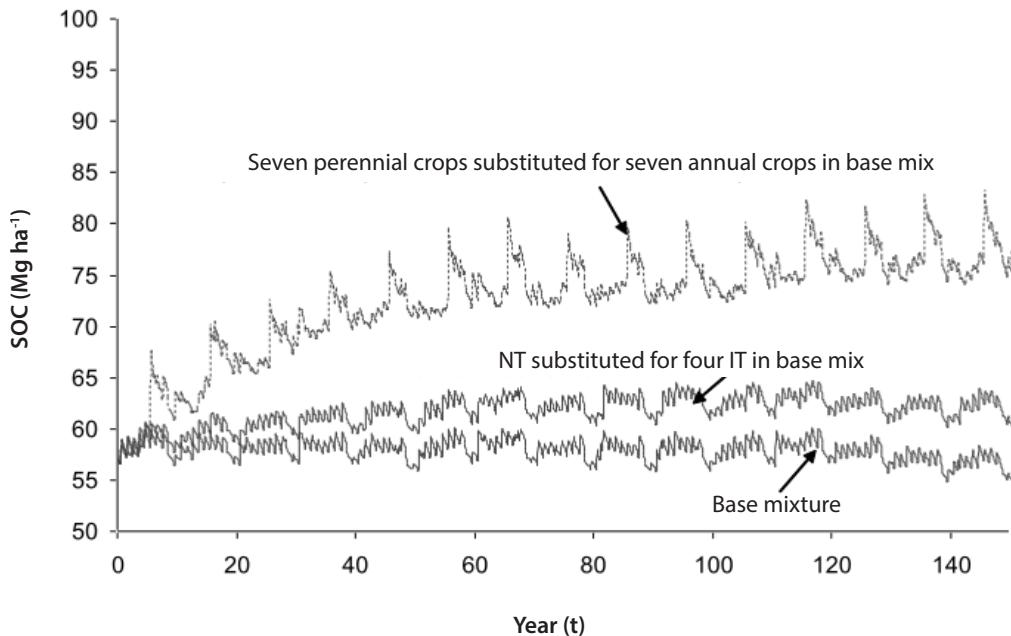
Figure A3.5-10 Method for Deriving Area-Based Carbon Factors for a Land Management Change of Interest



Note:

a. Cumulative C gain over time

Figure A3.5–11 Soil Organic Carbon (SOC) for a Base Crop Mix, for Perennial (Alfalfa) Substituted for Annual Crops (Wheat) and for No-Till (NT) Substituted for Intensive Till (IT) Based on Century Runs for a Lethbridge Loam



The SOC change factor is determined as Factor = (C for CTS with LMC – C for base CTS) / [(fraction of CTS substituted with the LMC) × (duration considered)]. If a land management system is defined as a particular mix of crops and tillage practices on a specified land area, a change in SOC due to an LMC (ΔC_{LMC}) can be estimated as the difference in SOC stock between two land management systems divided by the proportion of the land area subject to an LMC.

Equation A3.5–2

$$\Delta C_{LMC}(t) = \frac{\Delta C}{P_{LMC}}$$

$\Delta C_{LMC}(t)$	=	the change in SOC between land management systems in year "t" (Mg C ha ⁻¹)
ΔC	=	the change in SOC due to the LMC (Mg C)
P_{LMC}	=	the proportion of the land area under a given land management system subject to the LMC, ha

This proportion (P_{LMC}) can be derived as the proportion of the particular land management (LM) in the base system less the amount of the LM in the new system after the LMC.

Equation A3.5–3

$$P_{LMC} = P_{LMbase} - P_{LMnew}$$

P_{LMC}	=	the proportion of the land area under a given land management system subject to the LMC
P_{LMbase}	=	the fraction of land management of interest in the base land management system
P_{LMnew}	=	the fraction of land management of interest in the new land management system

The following provides an example of Century runs for a Lethbridge loam (Orthic Dark Brown Chernozem) in the Semi-arid Prairies reporting zone. A base model run was made using a 10-year base mix of crops based on the 1996 *Census of Agriculture* and weather data covering the years 1951–2000. Century simulations of SOC were made by substituting perennial crops for the 7 annual crops out of 10 in the base mixture. As a separate exercise, NT was substituted for IT 4 years out of 10 in the base mixture (Figure A3.5–11). The next step was to calculate the $\Delta C_{LMC}(t)$ function by subtracting the simulated SOC values for the base mix values from those imposed by the LMC of interest (Equation A3.5–2). Finally, the $\Delta C_{LMC}(t)$ was calculated as the proportion of area of farming system divided by the P_{LMC} . In this particular case of the time series of ΔC_{LMC} , the respective values of P_{LMC} for the IT to NT and for the addition of perennial crops were 4/10 and 7/10 (Figure A3.5–12).

SOC dynamics are believed to be governed by first-order kinetics, and thus C change can be expressed as:

Equation A3.5–4

$$\Delta C_{LMC}(t) = \Delta C_{LMCmax} \times [1 - \exp(-kt)]$$

$\Delta C_{LMC(t)}$	= the change in SOC due to the LMC at a time, t ($Mg\ C\ ha^{-1}$)
ΔC_{LMCmax}	= the maximum SOC change induced by the LMC ($Mg\ C\ ha^{-1}$)
k	= the rate constant, yr^{-1}
t	= year after LMC

In practice, the exponential equations are fit statistically using methods of least squares. The slope of the natural log transformed exponential equation has units of $Mg\ C\ ha^{-1}\ yr^{-1}$ and is the instantaneous factor value. Since the estimation is based on annual changes, the equation used for estimating the factor for annual change from the previous year (i.e., from year $t-1$ to year t) is:

Equation A3.5–5

$$F_{LMC}(t) = \Delta C_{LMCmax} \times [\exp\{-k \times (t-1)\} - \exp\{-k \times t\}]$$

$F_{LMC(t)}$	= the instantaneous C factor value due to the LMC at a time t, $Mg\ C\ ha^{-1}\ yr^{-1}$
ΔC_{LMCmax}	= the maximum SOC change induced by the LMC ($Mg\ C\ ha^{-1}$)
k	= the rate constant, yr^{-1}
t	= year after LMC

Figure A3.5–12 Change in SOC for Simulations with Substitutions Relative to Simulations with Base Crop Mix

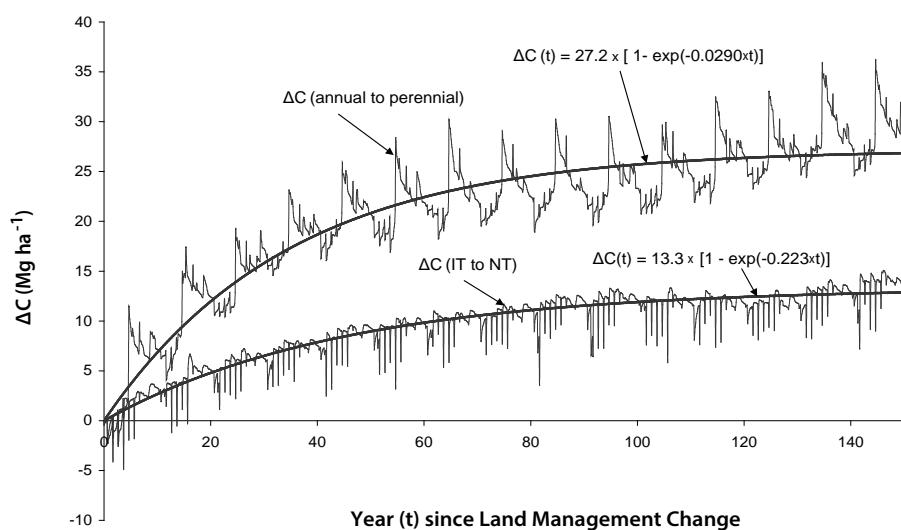
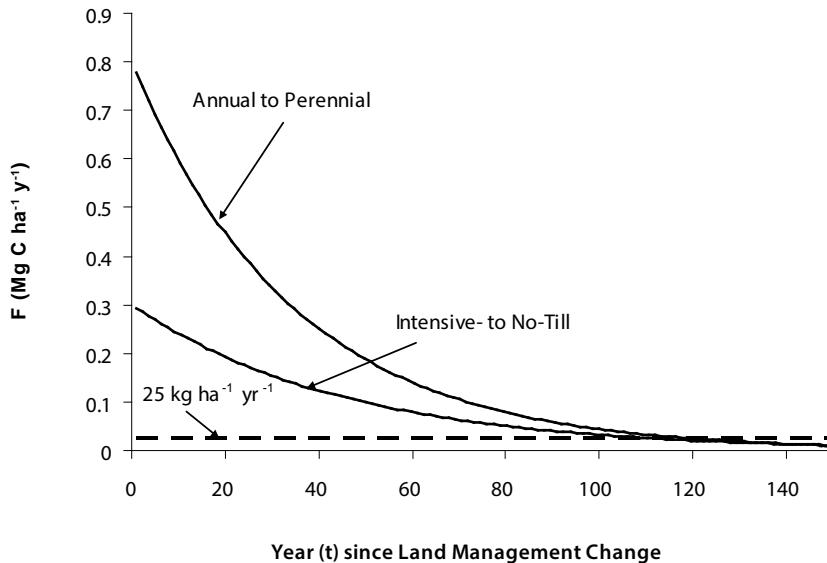


Figure A3.5–13 Carbon Factors as a Function of Time

A
3



Since perfect steady-state conditions are never reached, the exponential equation should theoretically apply forever. In practice, however, the exponential equation was truncated when the $F_{LMC}(t)$ dropped to $25 \text{ kg C ha}^{-1} \text{ yr}^{-1}$. This rate was below a practical measurement limit (Figure A3.5–13).

Estimating Mean k and ΔC_{LMCmax} for Practical Factor Calculations

The ΔC_{LMCmax} and k parameters were determined for all 11 602 soil components of the CanSIS database and two LMCs (changes in tillage practices and annual-perennial crop mix). These soil components represented a wide range of initial SOC states and combinations of base crop mixtures and amounts of substitutions. The parameter values were estimated for each reporting zone as the mean across these soil components, weighted by area of agriculture on each component (Table A3.5–8). The geometric mean was used for k , since its distribution was positively skewed. These means were calculated by three general soil texture classes (sandy, loamy and clayey) and applied to each soil component based on its textural class. Occasionally, k values less than 0 resulted from the fit to ΔC_{LMC} ; the k and ΔC_{LMCmax} from these fits were excluded from the reporting zone means.

Generally, rates of SOC losses following an LMC are expected to be greater than rates of SOC gain following the reverse LMC. However, this effect is highly dependent on the relative SOC amount at the time of the LMC. Documenting SOC at the time of all LMCs is currently impossible. Hence, for transparency and simplicity, the reversibility assumption was imposed, whereby the SOC effect of an LMC in one direction is exactly the negative of the SOC effect of the practice change in the opposite direction.

Area-Based Soil Carbon Factor Validation – Tillage and Crop Mixtures

SOC change factors for LMCs used in the inventory were compared with empirical coefficients in VandenBygaart et al. (2008). They showed that empirical data comparing SOC change between IT and NT were highly variable, particularly for Eastern Canada. Nonetheless, the modelled factors were still within the range derived from the empirical data. The mean IT-NT factor derived from experiments in the Subhumid Prairies reporting zone was over four times that of the Semi-arid Prairies reporting zone. The mean Century model-derived factor for the Semi-arid Prairies reporting zone was similar to the factor derived from the field experiments. However, the Century-derived IT-NT factor for the Subhumid Prairies reporting zone was about 30% lower than the factor derived from the field experiments.

When considering the switch from annual to perennial cropping, the mean empirical factor was 0.59 Mg C ha⁻¹ per year, which compared favourably with the range of 0.46–0.56 Mg C ha⁻¹ per year in the modelled factors in the Parkland, Semi-arid Prairies and West zones (Table A3.5–8). In Eastern Canada, only two empirical change factors were available in the East Central zone, but they appeared to be in line with the modelled values (0.60–1.07 Mg C ha⁻¹ per year empirical versus 0.74–0.77 Mg C ha⁻¹ per year modelled).

Crop Productivity/Crop Residue C Inputs

Grain yields of major field crops in Canada have increased steadily since 1970 (Figure A3.5–14). Accurate quantification of crop productivity and crop residue C input on SOC storage at regional or national scales over time relies on the use of spatio-temporal C input data. Estimating crop productivity/crop residue C input requires information on net primary productivity (NPP) and the proportion of NPP returned to the soil (Bolinder et al., 2007). NPP, measured as above-ground and below-ground plant biomass is calculated using crop yield information. Fan et al. (2017) analyzed yield and harvest index for 11 major crops from published field studies in temperate regions, and found significant linear relationships between harvest index and crop yield for wheat, maize, oat, barley, pea, chickpea, lentil, soybean, canola, and flax ($r^2 = 0.19\text{--}0.65$). These relationships between harvest index and crop yield were used to develop estimates of crop residue inputs. For other crops, crop residue C is estimated using allocation ratios among grain, straw and roots from Janzen et al. (2003). The inclusion of soil C change estimate as impacted by crop productivity/crop residue C input is fully aligned with crop residue nitrogen (N) estimates that result in soil N₂O emissions (See Annex A3.4.5).

Table A3.5–8 Effective Linear Coefficients of Soil Organic Carbon for Land Management Change (LMC)

Zone ^a	LMC ^{b,c}	k yr ⁻¹	ΔC_{LMCmax} (Mg ha ⁻¹)	Final Year of Effect after LMC ^d	Mean Annual Linear Coefficient over Duration of Effect of LMC (Mg ha ⁻¹ yr ⁻¹)	Mean Annual Linear Coefficient over First 20 Years after LMC (Mg ha ⁻¹ yr ⁻¹)
East Atlantic	IT to NT	0.0216	3.5	52	0.05	0.06
	IT to RT	0.0251	2.4	36	0.04	0.05
	RT to NT	0.0233	1.1	1	0.03	0
	Increase perennial	0.0217	43.4	167	0.25	0.77
East Central	IT to NT	0.025	5	65	0.06	0.1
	IT to RT	0.0261	1.9	25	0.04	0.04
	RT to NT	0.0255	3.2	46	0.05	0.06
	Increase perennial	0.0247	38.2	147	0.25	0.74
Parkland	IT to NT	0.0286	6.5	70	0.08	0.14
	IT to RT	0.0242	2.8	41	0.04	0.05
	RT to NT	0.0263	3.7	51	0.05	0.07
	Increase perennial	0.0233	29.4	142	0.2	0.55
Semi-arid Prairies	IT to NT	0.0261	4.9	63	0.06	0.1
	IT to RT	0.0188	2.3	30	0.03	0.04
	RT to NT	0.0222	2.5	37	0.04	0.05
	Increase perennial	0.0281	26.1	120	0.21	0.56
West	IT to NT	0.0122	4.8	69	0.04	0.05
	IT to RT	0.0116	0.8	0	0	0
	RT to NT	0.0119	3.9	53	0.03	0.04
	Increase perennial	0.0155	34.4	198	0.17	0.46

Notes:

Effective Linear Coefficients of SOC were generated using $F_{LMC(i)} = \Delta C_{LMCmax} \times [1 - \exp(-k \times t)]$.

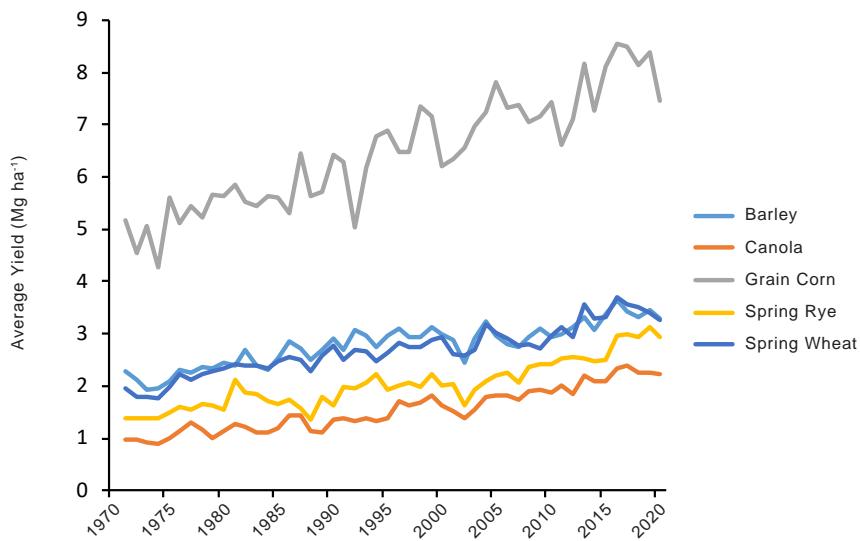
a. Area-weighted summary: East Atlantic is the Atlantic Maritime reporting zone plus the Boreal Shield reporting zone in Newfoundland and Labrador; East Central is the Mixedwood Plains reporting zone plus the Boreal Shield East reporting zone in Ontario and Quebec; Parkland is the Subhumid Prairies, Boreal Shield West and Boreal Plains reporting zones plus those parts of the Montane Cordillera reporting zone with agricultural activity contiguous to agricultural activity within the rest of the Parkland zone; and West is the Pacific Maritime reporting zone plus the Montane Cordillera reporting zone excepting that portion of the latter that is included in the Parkland zone as described above.

b. For LMCs in the opposite direction to that listed, the F_{LMCmax} will be the negative of the value listed.

c. IT = intensive tillage, RT = reduced tillage, NT = no-till

d. No further C changes once the absolute value of the rate of change is less than 25 kg C ha⁻¹ yr⁻¹.

Figure A3.5-14 Average Yields of Major Field Crops Grown in Canada from 1970 to 2020



Note:

Data source = Statistics Canada, 2020, Table 32-10-0359-01

Crop residue C input is estimated using annual crop yield, taking into account crop residual removal by field burning and baling by each field crop as follows:

Equation A3.5–6

$$CRC_i = \sum(CRC_AGR_{TC,i} + CRC_BGR_{TC,i})/T_AREA_i$$

CRC_i	=	crop residue C input estimated for all annual crops in ecodistrict i , from 1976 to 2020, Mg C $ha^{-1} yr^{-1}$
$CRC_AGR_{TC,i}$	=	total above-ground (AGR) crop residue C from crop type (TC) in ecodistrict i , Mg C
$CRC_BGR_{TC,i}$	=	total below-ground (BGR) crop residue C from TC in ecodistrict i , Mg C
T_AREA_i	=	total area of annual crops, including summerfallow, in ecodistrict i , ha

For major field crops, harvest index is estimated using a linear relationship with grain yield as reported by Fan et al. (2017).

Equation A3.5–7

$$HI_{TC} = YIELD_{TC,i} \times \left(1 - \frac{MC_{TC}}{100}\right) \times SLOPE_{TC} + INTERCEPT_{TC}$$

HI_{TC}	=	harvest index for crop type (TC), %
$YIELD_{TC,i}$	=	grain yield for TC in ecodistrict i , Mg ha^{-1}
MC_{TC}	=	moisture content of grain yield for TC, %
$SLOPE_{TC}$	=	linear regression coefficient for TC as specified in Fan et al. (2017)
$INTERCEPT_{TC}$	=	interception for TC as specified in Fan et al. (2017)

The dry matter portions of above-ground residue and roots for major field crops are estimated using the harvest index and root shoot ratio (Fan et al., 2017). For minor field crops, crop dry matter partitions among grain, above-ground residue and roots are calculated using the method proposed by Janzen et al. (2003).

Equation A3.5–8

$$\text{CRC_AGR}_{TC,i} = \left[\left\{ \sum PROD_{TC,i} \times \frac{PROD_{p,TC}}{\sum_{TC} (YIELD_{TC,i} \times AREA_{TC,i})} \right\} \times \left(1 - \frac{MC_{TC}}{100} \right) \times \frac{100}{HI_{TC,i}} \times \{1 - (BALE_{TC} \times 0.5 + BURN_{TC})\} \right] \times 0.45$$

$$\text{CRC_BGR}_{TC,i} = \left[\left\{ \sum PROD_{TC,i} \times \frac{PROD_{p,TC}}{\sum_{TC} (YIELD_{TC,i} \times AREA_{TC,i})} \right\} \times \left(1 - \frac{MC_{TC}}{100} \right) \times \frac{100}{HI_{TC,i}} \times RSR_{TC} \right] \times 0.45$$

$\text{CRC_AGR}_{TC,i}$	=	above-ground crop residue C for crop type (TC) in ecodistrict i , Mg C
$PROD_{TC,i}$	=	total grain production for TC in ecodistrict i , Mg
$PROD_{p,TC}$	=	total grain production for TC in province p , Mg
$\sum_{TC} (YIELD_{TC,i}) \times AREA_{TC,i}$	=	estimated grain production using average yield and seeded area for TC in ecodistrict i , Mg
MC_{TC}	=	moisture content of grain for TC, %
$HI_{TC,i}$	=	harvest index for TC in ecodistrict i , %
$BALE_{TC}$	=	crop residue baling for TC by assuming 50% of baling efficiency, fraction
$BURN_{TC}$	=	field burning of crop residue for TC, fraction
RSR_{TC}	=	root to above-ground crop residue ratio for TC, fraction
0.45	=	fraction of C in crop residue

SOC change Factors

The 2019 Refinement of the 2006 IPCC Guidelines (IPCC, 2019) provides a Tier 2 Steady State approach for estimating the change in SOC as impacted by crop productivity in Cropland Remaining Cropland (IPCC, 2019). This approach considers three conceptual C pools (active, slow, and passive) in the top 30 cm soil profile. Decomposition is driven by decay rates that depend on temperature and soil moisture. Soil texture and tillage practices alter the decomposition of the active and slow C pools. Further details on this model are discussed by Ogle et al. (2012). The approach of IPCC Tier 2 Steady State model requires lignin and N content of the C inputs (IPCC, 2019). The model is initialized using the first 10-year C inputs according to the IPCC guidance (IPCC, 2019). Average soil C stocks at the initiation of the model simulation were extracted from the National Soil Database³⁶ (NSDB, Version 3.2) for the dominant soil series of each textural class by ecodistricts.

Figure A3.5–15 provides a schematic representation of soil C estimation procedures as impacted by crop productivity/crop residue C input.

The IPCC Tier 2 Steady State approach was applied for Canadian soils to calculate the factor that estimates the change in soil C associated with crop productivity. The change in SOC is calculated by applying a ΔSOC factor weighted by proportions of textural class in each ecodistrict to total area in an ecodistrict for each of the consecutive years from 1976 to 2020. These estimates were combined with LMC factors for tillage and annual/perennial crop mixtures. The total C change for an ecodistrict is then generated by summing SOC change values across all textural classes present in the ecodistrict (Equation A3.5–9).

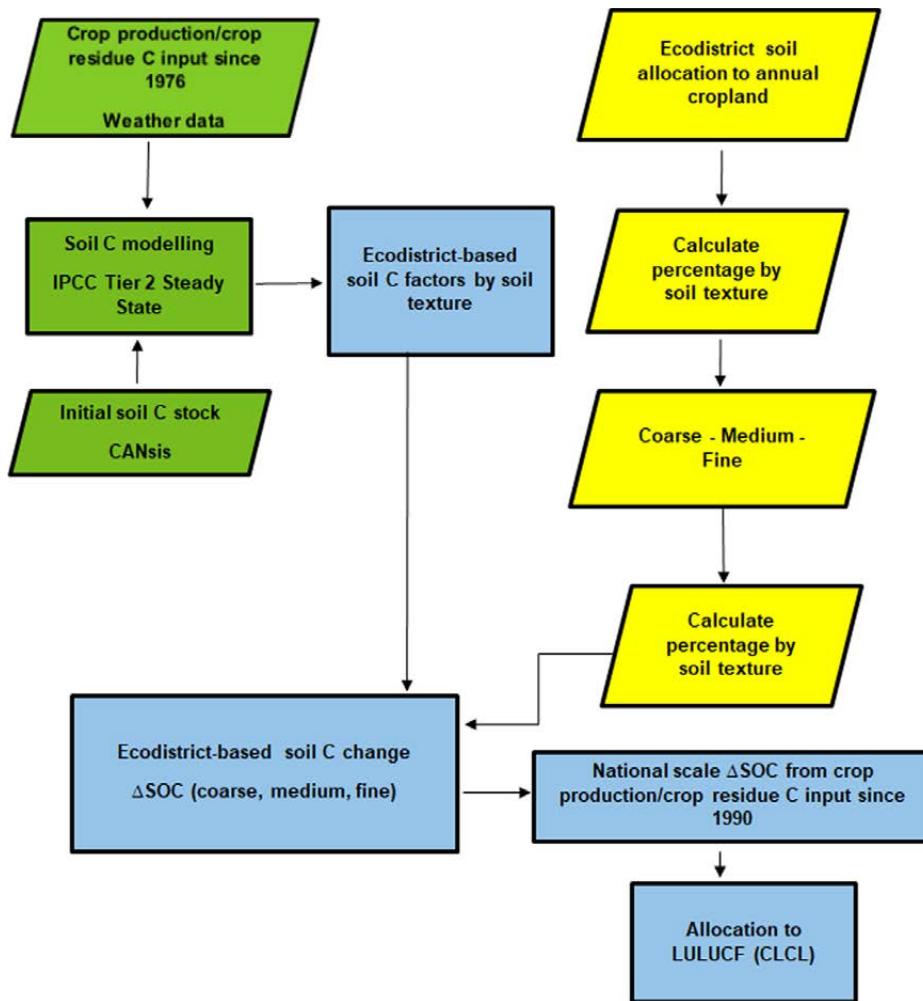
Equation A3.5–9

$$\Delta SOC_{t,i} = \sum \{(SOC_{t,TX,i} - SOC_{t-1,TX,i}) \times TF_{t,TX,i}\} \times T_AREA_{t,i}$$

$\Delta SOC_{t,i}$	=	change in soil organic carbon (SOC) in ecodistrict i , and year t , Mg C
$SOC_{t,TX,i}$	=	SOC stock associated with soil texture class (TX) in year t and ecodistrict i , Mg C ha ⁻¹
$SOC_{t-1,TX,i}$	=	SOC stock associated with soil TX in year $t-1$ and ecodistrict i , Mg C ha ⁻¹
$TF_{t,TX,i}$	=	soil texture fraction in coarse, medium and fine, TX in ecodistrict i and year t , fraction
$T_AREA_{t,i}$	=	total area of annual crops, including summerfallow, in ecodistrict i and year t , ha

36 Available online at: <https://sis.agr.gc.ca/cansis/nsdb/index.html>

Figure A3.5-15 A Representation of Procedures for Estimating Soil Organic Carbon Changes as Impacted by Crop Productivity/Crop Residue Carbon Input



Note:

CLCL = Cropland Remaining Cropland

Due to lack of certainty in the real C stocks and to maintain consistency with the other C factors, the method only reports the change in C since 1990, consistent with the area-based factor approach. The period from 1976 to 1989 is considered as a reference baseline and the mean change in C stocks due to the change in crop productivity (ΔC_{CP}) values from the reference period are then added to the ΔC_{LMC} values.

Manure Application

The application of animal manure on agricultural soils can increase SOC storage, particularly when manures are transferred to soils under annual crop production. Manure-induced C retention (MCR) represents the average fraction of C input from various manures that is retained in the soil. This factor was established from the measurements taken from multiple long-term studies. A country-specific method using MCRs is proposed to estimate soil C sink change as a result of manure application to cropland soils in Canada. Eight field studies using various types and rates of manure application on different crop rotations, with durations varying from 10 to 74 years, were used to quantify MCRs across diverse climatic conditions in Canada. Solid cattle and swine manure had an MCR of 26%, whereas the MCR for liquid manure, including swine and cattle liquid manures, was much smaller, at only 5%. Compared to stockpiled manures, composted manure had a higher MCR of 36% due to the additional stabilization of C during the composting process (Liang et al., 2021). The use of individual MCRs for different manure types provides a sound approach for quantifying changes in soil C storage resulting from manure applications at a regional or national scale. Based on the study of Liang et al. (2021) this approach is judged to be more accurate than the IPCC default ratio factors that are based on a qualitative measure of “manure input” (IPCC, 2006) for Canadian conditions.

Other variables required for estimating soil C storage from manure application include livestock populations, manure N excretion, and manure N losses during storage and handlings (ammonia volatilization and N leaching). These data are consistent with data used for the Enteric Fermentation and Manure Management categories reported in the Agriculture sector (see Annex A3.4). The amount of C in the manure was estimated using C:N ratios compiled through the literature review (Table A3.5–9).

Equation A3.5–10

$$\Delta C_{ManureC} = \sum (ManureN_{T,AWMS,i} \times CN_{T,AWMS}) \times MCR_{T,AWMS}$$

$\Delta C_{ManureC}$	=	amount of soil C gain from manure application, kg ha ⁻¹ yr ⁻¹
$ManureN_{T,AWMS,i}$	=	amount of manure N applied in ecodistrict i, for livestock type (T) and animal waste management system (AWMS) on annual crop, kg N ha ⁻¹ yr ⁻¹
$CN_{T,AWMS,i}$	=	C:N ratio of applied manure for T and AWMS, unitless as specified in Table A3.5–9
$MCR_{T,AWMS}$	=	manure-induced C retention for T and AWMS, fraction, as specified in Liang et al. (2021)

Estimates of Change in Soil Carbon Stocks

SOC changes as a result of LMC were reported for all inventory years since 1990. Because the effect of LMCs declines over time, a time period when change was deemed to have occurred is maintained for each LMC. The C change factor was multiplied by the area of LMC and summed across soil components to produce an estimate of SOC change for the SLC polygon. This is the smallest georeferenced unit of SOC stocks and SOC stock changes calculated using an IPCC Tier 2 approach as follows:

Equation A3.5–11

$$\Delta C_{LMC} = \sum_{1990-n} \sum_{ALL Ecod} (\Delta C_{TILL} + \Delta C_{CP} + \Delta C_{CROPPING} + \Delta C_{ManureC})$$

ΔC_{LMC}	=	change in SOC stocks due to LMC for a specific year since 1990 until year n (latest inventory year)
$ALL Ecod$	=	all ecodistricts that contain land management practices in cropland remaining cropland
ΔC_{TILL}	=	change in SOC stocks due to change in tillage practices from each ecodistrict, since each particular tillage change
ΔC_{CP}	=	change in SOC stocks due to the change in crop productivity/crop residue C in each ecodistrict
$\Delta C_{CROPPING}$	=	change in soil C stocks due to the change in annual and perennial crops in each ecodistrict
$\Delta C_{ManureC}$	=	change in soil C stocks due to the change in manure application in each ecodistrict

Table A3.5–9 C:N Ratios of Applied Manure from Major Livestock Types and Manure Management Systems on Agricultural Soils

Livestock	Manure Type	C:N Ratio ^a	References
Dairy Cattle	Liquid	15.0 (± 7.3)	Bhandral et al. (2009); Rochette et al. (2008); Pelster et al. (2012); Lynch et al. (2005); Maillard et al. (2015); Maillard et al. (2016); Aoyama et al. (1999)
	Solid	13.1 (± 1.4)	Rochette et al. (2008)
Beef Cattle	Solid	14.1 (± 4.7)	Hao et al. (2003); Sommerfeldt et al. (1988); Izaurralde et al. (2001); Grant et al. (2001); Pare et al. (1999); Larney and Janzen (1996)
Swine	Liquid	10.5 (± 2.4)	Pelster et al. (2012); Chantigny et al. (2000); Chantigny et al. (2007); Chantigny et al. (2010); Chantigny et al. (2012)
Poultry	Solid	5.0 (± 0.4)	Pelster et al. (2012); Forge et al. (2016); Rees et al. (2014); Larney and Janzen (1996)

Note:

a. Numbers in the parentheses are standard deviations

Figure A3.5–16 provides a schematic of the methods for C estimation.

Data Sources

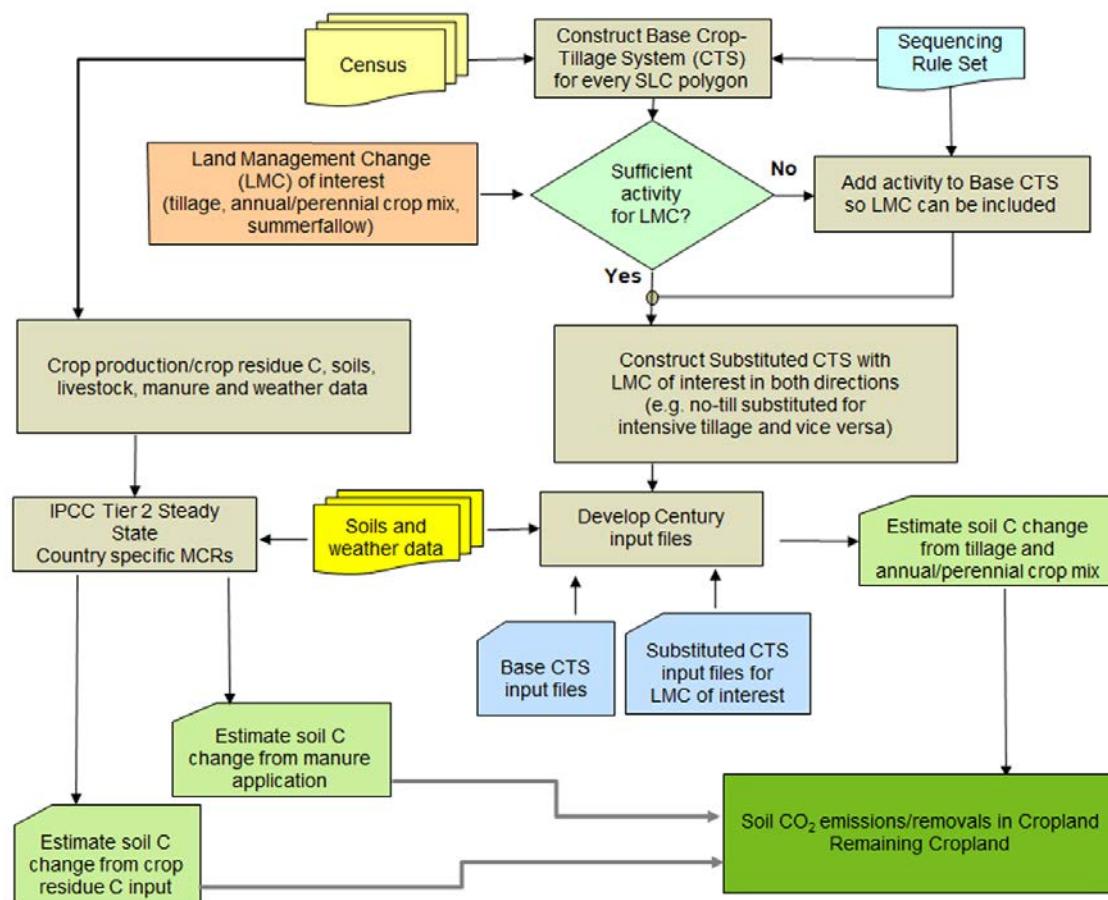
Carbon stock change estimates rely on C factors and a time series of land management data in the *Census of Agriculture*. There are two types of data used for either deriving C factors (modelling) or computing the actual estimates of soil C stock change. The main data used for modelling C factors include SLC, crop-tillage systems derived from the *Census of Agriculture*, crop yields, climatic data and activity data from other surveys and databases. The main data used for estimating annual soil C stock changes are data on land management practices from the *Census of Agriculture*.

Land Information and Activity

The SLC is a national-scale spatial database describing the types of soils associated with landforms, displayed as polygons at an intended scale of representation of 1:1 million.³⁷ The SLC was chosen for the LULUCF inventory because of its national scope and standardized structure, which ensure that all areas of the country are treated in a consistent manner with regard to inventory assessment procedures. The current version of the SLC in the National Soil Database (NSDB) data holdings is version 3.2. The extent of the soil attribute information in this coverage is restricted primarily to the agricultural areas of Canada. In instances where agricultural land was mapped outside the coverage of SLC v3.2, then soil attribute information was extracted from SLC v2.2, an older but complete coverage of soils in Canada. All SLC polygons are “nested” within the 1995 National Ecological Framework, making it possible to scale up or scale down data and estimates, as required.

³⁷ Available online at <http://sis.agr.gc.ca/cansis>.

Figure A3.5–16 Method of Using Area-Based and Input-Based Factors for Land Management Change to Estimate Carbon Change in Canada



In all provinces within the agricultural region of Canada, detailed soil survey information with map scales greater than 1:1 million was used to delineate the SLC polygons and compile the associated database files. The SLC Component Soil Names Tables and Soil Layer Tables provided specific input data, including soil C content, soil texture, pH, bulk density and soil hydraulic properties for modelling C factors with Century. The SLC polygon provides the spatial basis for allocating land management practices, such as tillage practices and cropping systems from the *Census of Agriculture* and Cropland converted from Forest Land and Grassland, to modelled C factors. The estimated areas of cropland and other land-use practices on an SLC polygon basis were derived from EO-based maps for 1990, 2000, 2005, 2010, and 2015.

Analysis Units

There are 3475 SLC polygons in which agricultural activities occur. Since the SLC polygons have several soil landscape components, the finest spatial resolution for analysis of agricultural activities is 13 771 unique combinations of soils, landforms and slope positions within SLC polygons. These unique combinations represent the basic analysis units. The location of land management and soil components is not spatially explicit but rather spatially referenced to SLC polygons.

A procedure was developed to assign agricultural activities to the SLC based on the suitability of each component of a soil polygon. The soil components have different inherent properties that make them more or less likely to be used for specific types of agricultural activities. Each soil component within the SLC attribute file has a suitability rating of high, moderate or low in terms of its likelihood of being under annual crop production. In this way, annual crop production is linked to those soils with a high rating. If there was insufficient area with high likelihood of being under annual cropland to be assigned to annual crop production, the remaining annual crop production will be assigned to components with moderate likelihood of being under annual crop production and, if required, to low-ranked components. After the annual crop production area was linked, perennial forages and seeded pasture area were linked to the remaining components in the same manner, starting with components with the highest likelihood of being in annual crops and ending with components with the lowest likelihood of being cropped.

Crop Yields

Crop yields at an ecodistrict level were developed from Statistics Canada surveys. Statistics Canada conducts annual surveys of up to 31 000 farmers, stratified by region, to compile estimates of the area, yield, production and stocks of the principal field crops grown in Canada. Several publications are released at strategic points in the crop year. Yields and levels of production by province are estimated twice, based on expectations to the end of harvest, whereas the November estimate is released after the harvest. The data are released at the census small area data (SAD) region level, providing crop yields for approximately 70 spatial units in the country. Census SAD region boundaries were overlaid on SLC boundaries in a GIS, and a yield value for each crop in each soil polygon was assigned based on majority proportion. Data used to calibrate the Century crop growth submodel included 1975–2004 yield data for wheat, barley, oats, corn, soybeans, potatoes and canola. Data used for crop C input modeling included all crop yield data since 1976. In cases where crop yields were not available at the SAD region level, provincial yield statistics were used.

Those yields were used to calibrate the Century crop growth submodel for area-based factors.

The amount of crop residue C that is returned to the soil at an ecodistrict scale since 1976 was quantified annually based on crop production (Statistics Canada, 2020). Crop residue baling for various field crops is collected by Statistics Canada, through Farm Environment and Management Survey (FEMS). Data on field burning of crop residues are also available (See Annex A3.4.7). Crop residue input is consistent with crop residue calculations used in the calculation of N₂O emissions in Chapter 5, Agricultural Soils.

Climatic Data

There are 958 weather stations in the database archived by Agriculture and Agri-Food Canada (AAFC). Long-term normals of monthly maximum and minimum temperatures (T, °C) and precipitation (mm) from 1951 to 2000 for all ecodistricts were used for area-based modelling of C factors. For inputbased models, the Environment and Climate Change Canada (ECCC) weather database (1981–2010) was used to be consistent with climate parameters used in the N estimation methodology. Application of the IPCC Tier 2 methodology further required Tmax, Tmin, Tavg, precipitation and potential evapotranspiration (PET). AAFC-archived weather data were provided by ECCC's Meteorological Service of Canada.

Earth Observation and the *Census of Agriculture*

Activity data for C estimation in the Cropland Remaining Cropland category rely mainly on a combination of data from the *Census of Agriculture* and area estimates based on EO analyses. The *Census of Agriculture* is conducted every five years to develop a statistical portrait of Canada's farms and agricultural operators. For confidentiality reasons, the smallest area for which Statistics Canada externally releases data from the *Census of Agriculture* is the dissemination/enumeration area level (of which there are approximately 52 000 in Canada). To provide a biophysical basis on which to model, data at this level were attributed to the SLC polygons (McConkey et al., 2007a).

Mapping data based on EO were used to provide area estimates of all land-use practices within each of the agricultural SLCs in Canada. Land-use maps based on EO information were generated for 1990, 2000, 2005, 2010 and 2015 (Huffman et al., 2015a; AAFC, 2021). Using SLC polygons as the level of spatial stratification, data were compiled into seven primary land cover categories: cropland, grassland, forest land, settlements, wetlands, water, and other land. From 1990 to the latest inventory year, annual estimates of land-use areas were generated by interpolating between EO years and extrapolating beyond the last year of coverage. Agricultural land-use estimates prior to 1990 were generated using the *Census of Agriculture* and the relative change in cropland and grassland areas between census periods. Land-use estimates for 1981 were generated by calculating the relative change in agricultural land use with the use of data from the 1991 and 1981 censuses and applying this change to the 1990 EO data. Then, moving progressively back through periods between census years, the relative changes were used to generate agricultural land-use estimates back to 1951. To minimize spatial variability associated with known issues related to reporting land-use areas based on farm headquarters, the relative change in land-use estimates was calculated at the spatial scale of the ecodistrict and applied to all SLC polygons nested within.

The EO-based cropland attributes were estimated using ratios of cropland area attributes to total cropland area from the *Census of Agriculture*. To reduce differences between EO and census estimates of provincial crop areas, EO cropland categories (i.e., cropland, pasture, orchards and vineyards) were reconciled using provincial scaling factors. Reconciliations were constrained by the total area of agricultural land within SLC polygons, as interpreted through EO analysis. Data on tillage management practices were taken from the *Census of Agriculture* according to the following categories: IT—tillage that incorporates most of the crop residue into the soil, RT—tillage that retains most of the crop residue on the surface, and NT—no-till seeding or zero-till seeding. For summerfallow, the following tillage categories were used: NT—the area on which chemicals only were used for weed control, IT—the area on which tillage only was used, and RT—the area on which a combination of tillage and chemicals was used. More technical details on the methodological approach used to create the EO-based agricultural activity data are provided in Cerkowniak (2019).

Uncertainty

The derivation of uncertainties about estimates of CO₂ emissions or removals requires estimates of uncertainties for LMC areas and the C factors associated with changes in tillage and annual/perennial crops (McConkey et al., 2007b). The uncertainty described in this report is based on the 2014 submission methodology and has not yet been updated for the new EO methodology.

The uncertainty of area of change was determined for ecodistricts. The average area of agricultural land within an ecodistrict is about 140 kha, i.e., sufficiently large that the areas of different management practices were considered independent of those in others, including adjacent ecodistricts. Errors in the areas of management practices in each ecodistrict were assumed to represent inherent uncertainty that was unaffected by the uncertainty of those in other ecodistricts. Further, the ecodistrict area is sufficiently large that a null report of an activity can be assumed to mean that the activity is not occurring within the ecodistrict. Therefore, area uncertainty can be more reliable when considered in relative terms for an ecodistrict than for an SLC polygon.

The uncertainty of the area in a management practice at any time for an average ecodistrict was based on the relative proportion of the area of that management practice in that ecodistrict. The relative uncertainty of the area of a management practice expressed as standard deviation of an assumed normal population decreased from 10% of the area to 1.25% of the area as the relative area of that practice increased.³⁸

The uncertainties associated with C change factors for fallow, tillage and annual/perennial crops were assumed to arise from two main influences: 1) process uncertainty in C change due to inaccuracies in predicting C change even if the situation of the management practice was to be defined perfectly, and 2) situational uncertainty in C change due to variation in the situation of the management practice.

Process uncertainty includes the effect of uncertainty in the model. This includes the uncertainty in the model predictions from uncertain model parameters and from inaccurate and/or incomplete representation of all relevant processes by the model. Where empirical data are used, process uncertainty includes inadequacies in measurement techniques, analysis error, poor representativeness of measurements and/or components of C change not measured. To estimate the process error, the variation from measured C change for controlled experiments was used. It was assumed that this represents the inherent uncertainty even when the situation is accurately described. Process uncertainty scaling coefficients for tillage and fallow were derived for Canada from VandenBygaart et al. (2003).

Situational uncertainty derives from the inability to accurately describe each situation. This includes the effect of interactions with past or concurrent changes to land use or land management, variability in the weather or soil properties, variability in crop management and/or continuity of LMCs. The situational uncertainty scaling coefficients for fallow change, tillage change and annual-perennial crop change were estimated from the observed variability of Century-simulated C change for all soil component-management-climate combinations within the RU. There were many combinations of management

³⁸ Huffman T. 2006. Personal communication (from Huffman T, Agriculture and Agri-Food Canada to McConkey BG, Agriculture and Agri-Food Canada).

within which C change was calculated. There was also a range of historical ecodistrict weather data that was included in the Century simulations. The situational uncertainty also includes the additional variability of the regional factors introduced by the imposition of reversibility of C change. Average situational uncertainty scaling coefficients were derived for Canada (McConkey et al., 2007b).

Although process and situational uncertainty are expected to interact, it is infeasible to describe their relationship given the complexity of the large number of possible interactions between deviations due to process uncertainty and those due to situation uncertainty. Hence, it was assumed that the total deviation in total C change was the sum of the deviation from process and situational uncertainty. Details of uncertainty estimate development are provided in McConkey et al. (2007b). Results of this analysis are provided in Chapter 6.

A formal uncertainty analysis has not yet been carried out for the estimates of cropland C change associated with changes in crop yield. However other soil C models of varying complexities (i.e. Rothamsted carbon model (RothC), Introductory Carbon Balance Model (ICBM), and CAMPBELL) that are capable of using measured yield as C inputs in simulations were tested in the national C assessment analysis. These models were also used for simulations on SOC with a varying degree of success against field observations (Thiagarajan et al., in prep.). Estimates of national C change varied from a loss of 5.4 Mt C in 1990 to a gain of 4.4 Mt C in 2020 by the CAMPBELL model, and a gain of 9.9 Mt C in 1990, to 38.5 Mt C in 2020 by ICBM. For a comparability among Annex 1 Parties, the IPCC Tier 2 approach is used for estimating the change in SOC as impacted by crop productivity/crop residue C input at a spatial scale of ecodistrict, RU and Canada. The results of this approach were observed to be roughly equivalent to the mean of the other models suggesting that the approach provides estimates within the bounds of what has been typically observed in other studies, as represented by the default parameters of existing soil C models.

Similarly, a formal uncertainty analysis has not been conducted for the estimates of cropland C change from manure application, though uncertainty estimates associated with field measurements of MCRs are available; $\pm 30\%$ for solid swine and cattle manure, $\pm 13\%$ for swine manure compost, and $\pm 330\%$ for liquid swine and cattle manure. Discussions of uncertainties associated with livestock type and population, and manure excretion as well as C:N ratio of various types of applied manures can be found in sections A3.4.1, A3.4.3 and Table A3.5–9.

CO₂ Emissions and Removals from Woody Biomass

Estimates of emissions and removals from woody biomass on croplands include those originating from trees and shrubs in agricultural land as well as vineyards, fruit orchards and Christmas trees. A remote sensing-based sampling approach was used to determine areas of trees and shrubs over the reporting period, whereas the *Census of Agriculture* was used to acquire area estimates of vineyards, fruit orchards and Christmas trees.

Vineyards, fruit orchards and Christmas tree farms are intensively managed for sustained yields. Vineyards are pruned each year, leaving only the trunk and one-year-old stems. Similarly, fruit trees are pruned annually to maintain the desired canopy shape and size. Old plants are replaced on a rotating basis for disease prevention, stock improvement or introduction of new varieties. Typically, Christmas trees are harvested at about 10 years of age. For all three crops, it was assumed that, because of these rotating practices and the requirements for sustained yield, a uniform age-class distribution is generally found on production farms. Hence, there would be no net increase or decrease in biomass C within existing farms, as C lost from harvest or replacement would be balanced by gains due to new plant growth. The approach was therefore limited to detecting changes in areas under vineyards, fruit orchards and Christmas tree plantations and estimating the corresponding C stock changes in total biomass.

There are no Canadian studies on the above-ground or below-ground C dynamics of vineyards or fruit trees. However, results from other studies are considered valid inasmuch as varieties, field production techniques and even root stocks are often the same. Canadian literature on Christmas tree plantations is used whenever suitable.

On average, vines are replaced at 28 years of age; the average vine is therefore 14 years old (Mailvaganam, 2002). Because of intensive pruning, linear rates of above-ground and below-ground biomass accumulation in trunks and roots were set at 0.4 and 0.3 Mg ha⁻¹ yr⁻¹, respectively (Nendel and Kersebaum, 2004). These were converted to C values using a 50% C content in biomass. Upon a decrease in vineyard areas, an instantaneous loss of 4.9 Mg C ha⁻¹ is assumed, equal to the average standing biomass for 14-year-old vines (McConkey et al., 2007a).

Because of different standard planting densities, the range of standing biomass per area for apple and peach trees varied narrowly between 36 and 40 Mg ha⁻¹ (McConkey et al., 2007a). This similarity is expected since, regardless of tree size and planting density, the tree shapes and canopies are manipulated to maximize net photosynthesis per area. An annual rate of C sequestration was calculated over a 10-year growth period at 1.6 Mg C ha⁻¹ yr⁻¹. The same rate, multiplied by a root to shoot ratio of 0.4 (Bartelink, 1998), was used to estimate C sequestration in below-ground biomass. Instantaneous C loss upon a decrease of orchards was equal to 50% of the total biomass of a 10-year-old tree (22.4 Mg C ha⁻¹).

Christmas trees are marketed at about 10 years of age (McConkey et al., 2007a). With a root to shoot ratio of 0.3 (Bartelink, 1998; Litton et al., 2003; Xiao and Ceulemans, 2004), the total C biomass of a marketable tree plantation is estimated at 11.1 Mg C ha⁻¹. Carbon sequestration in biomass of new Christmas tree plantations is calculated for five years at rates of 0.85 and 0.26 Mg C ha⁻¹ for above-ground and below-ground biomass, respectively. A decrease of plantation area would result in the immediate loss of 5.6 Mg C ha⁻¹.

Trees and shrubs in agricultural land include perennial woody cover types in farmyards, shelterbelts and hedgerows. Carbon storage on the landscape in woody biomass changes over time as trees and shrubs grow and die, or areas of lands with woody biomass change due to planting or colonization of cropland areas or the clearing of trees.

The EO-based sampling approach used to quantify changes in woody biomass on Canadian croplands was developed by Huffman et al. (2015b). Briefly, the national ecological framework (Marshall et al., 1999) was used to develop a spatially stratified random sampling approach. A target of 30 sample sites per ecozone was identified. High-resolution historical aerial photos from the National Air Photo Library of Natural Resources Canada and from provincial databases were selected to digitize trees and shrubs land cover within a 2 km by 2 km plot for circa 1990, circa 2000 and circa 2010 at 1:10000 scale. The “trees” land cover class was defined as having less than 25% crown closure and being less than 1 ha in size. The “shrubs” land cover class represents non-agricultural woody plants that would not be expected to meet the forest or “trees” definition when mature. Wood volume yield estimates for each ecozone were derived based on published literature and consultations with provincial forestry and agriculture specialists, conservation associations and academia. Overall, estimates of above-ground wood volume varied between 99.3 and 181.7 m³ ha⁻¹ across ecozones, and mean annual increments varied between 1.2 and 3.8 m³ ha⁻¹ yr⁻¹. With the addition of a new dataset in 2020, the growth, loss and gain in the biomass of trees and shrubs (in tonnes of C) were calculated for two time periods: 1990–2000 and 2000–2010 in croplands. The analysis, coefficients and parameters used to estimate C stock changes were based on the methodology described by Huffman et al. (2015b) for both time periods

Analysis of firewood production suggested that agricultural lands serve as an important source for residential bioenergy production in Canada (Doyon et al., 2019). A portion of the tree biomass loss from cropland was therefore transferred to the HWP pool as firewood input to meet regional residential bioenergy requirements (see section A3.5.3) at the RU level. Further in regions where there was a shortage of supply in the forest biomass in a given RU, fractions of lost tree biomass from cropland were assumed to be sourced from the neighbouring RU. To avoid double counting of emissions between the Cropland and Harvested Wood Products categories, the amount of C transferred to the HWP pool was not reported as C loss under Cropland, normally being reported as instant oxidation. As a result an apparent higher sink or reduced emissions from woody biomass is reported, though once considering the transfer to HWP, no net change in total C emissions or removals occurs.

Uncertainty

Poorly growing orchards and vineyards are regularly removed and replaced. Frequently, fruit trees and vineyards are irrigated to maintain desired growth during dry periods. Consequently, the variability in C stock changes should be less than that for other agricultural activities.

For loss of area, all C in woody biomass is assumed to be immediately released. There are no Canadian-specific data on uncertainty for vineyards, orchards and Christmas trees. Therefore, the default uncertainty of ±75% for woody biomass on cropland from the 2006 IPCC Guidelines was used for these land cover types. An error propagation approach described in Huffman et al. (2015b) was applied for trees and shrubs. If the loss in area of fruit trees, vineyards or Christmas trees is estimated to have gone to annual crops, there is also a deemed perennial-to-annual crop conversion with associated C change uncertainty that contributes to C change uncertainty for a reporting zone.

Cultivation of Organic Soils

Cultivation of histosols for annual crop production usually involves drainage, tillage and fertilization. All these practices increase decomposition of SOC and, thus, release of CO₂ to the atmosphere.

Methodology

The IPCC Tier 1 methodology is based on the rate of C released per unit land area:

$$C = \sum(A_i \times EF)$$

C	= C emissions from cultivation of organic soils (Mg C yr ⁻¹)
A_i	= area of organic soils that is cultivated for annual crop production in province <i>i</i> , ha
EF	= C emission factor, Mg C loss ha ⁻¹ yr ⁻¹ . The default EF of 5.0 Mg C ha ⁻¹ yr ⁻¹ was used (IPCC, 2006).

Data Sources

Areas of cultivated histosols at a provincial level are not included in the *Census of Agriculture*. In the absence of these data, consultations with numerous soil and crop specialists across Canada were undertaken. Based on these consultations, the total area of cultivated organic soils in Canada was estimated at 16 kha (Liang et al., 2004).

Uncertainty

The uncertainty associated with emissions from this source is due to the uncertainties associated with the area estimates for the cultivated histosols and of the emission factor. The 95% confidence limits associated with the area estimate of cultivated histosols are assessed to be ±50%. The 95% confidence limits of the emission factor provided in the 2006 IPCC Guidelines (IPCC, 2006) is ±90%.

A3.5.4.2. Grassland Converted to Cropland

Conversion of native grassland to cropland results in losses of SOC and soil organic nitrogen (SON) and in turn leads to emissions of CO₂ and N₂O to the atmosphere. According to a study on the burning of managed grassland in Canada by Bailey and Liang (2013), C changes from above-ground or below-ground biomass or DOM upon conversion are generally insignificant. The authors reported that the average above-ground biomass was 1100 kg ha⁻¹ in the Brown Chernozem and 1700 kg ha⁻¹ in the Dark Brown Chernozem. The above-ground biomass for the managed grassland would be lower than its yield under crop production (Liang et al., 2005).

A number of studies on changes of SOC and SON in grassland converted to cropland have been carried out on the Brown, Dark Brown and Black soil zones of the Canadian Prairies, and their results are summarized by McConkey et al. (2007a).

Losses of Soil Organic Carbon

The average loss of SOC based on field observations was 22% (McConkey et al., 2007a). Many of the studies involved comparisons within 30 years of breaking of the native grassland, whereas others were 70 or more years from breaking. Since many of these studies did not specify the period since breaking, it is assumed that the 22% SOC loss would refer to about 50–60 years after the land was broken.

The SOC dynamics from breaking of grassland to cropland for the Brown and Dark Brown Chernozemic soils (Figure A3.5–17) can be estimated with the Century model (Version 4.0). Shortly after breaking, there is an increase in soil organic matter, as below-ground biomass of the grass becomes part of SOC. After a few years, SOC declines below the amount of SOC that existed under grassland. The rate of SOC decline gradually decreases with time. Neglecting the initial SOC increase due to C added from roots, simulated SOC dynamics can be described by the following equation:

$$\Delta C(t) = \Delta C_{Bmax} \times [1 - \exp\{-k \times (t - t_{lag})\}]$$

ΔC(t)	= change in SOC for the <i>t</i> th year after conversion, Mg C ha ⁻¹
ΔC_{Bmax}	= ultimate change in SOC from grassland to cropland, Mg C ha ⁻¹
k	= rate constant for describing the decomposition, yr ⁻¹
t	= time since breaking of grassland, years
t_{lag}	= time lag before ΔC becomes negative, years

Assuming that the 22% loss at about 50–60 years after initial breaking represents the total loss, the $\Delta C_{B\max}$ is $0.22/(1-0.22) = 28\%$ of the stabilized SOC under an agricultural land use. Given the uncertainty of actual dynamics, it was assumed that there was no time lag in SOC loss from breaking grassland, so that SOC starts to decline immediately upon breaking. With these assumptions, the general equation for predicting SOC loss from breaking grassland becomes:

Equation A3.5–14

$$\Delta C(t) = 0.28 \times SOC_{agric} \times [1 - \exp(-0.12 \times t)]$$

$\Delta C(t)$	=	change in SOC for the t th year after conversion, Mg C ha ⁻¹
t	=	time since breaking, years
SOC_{agric}	=	0- to 30-cm SOC from the National Soil Database within CanSIS under an agricultural land use (Cropland category), Mg C ha ⁻¹

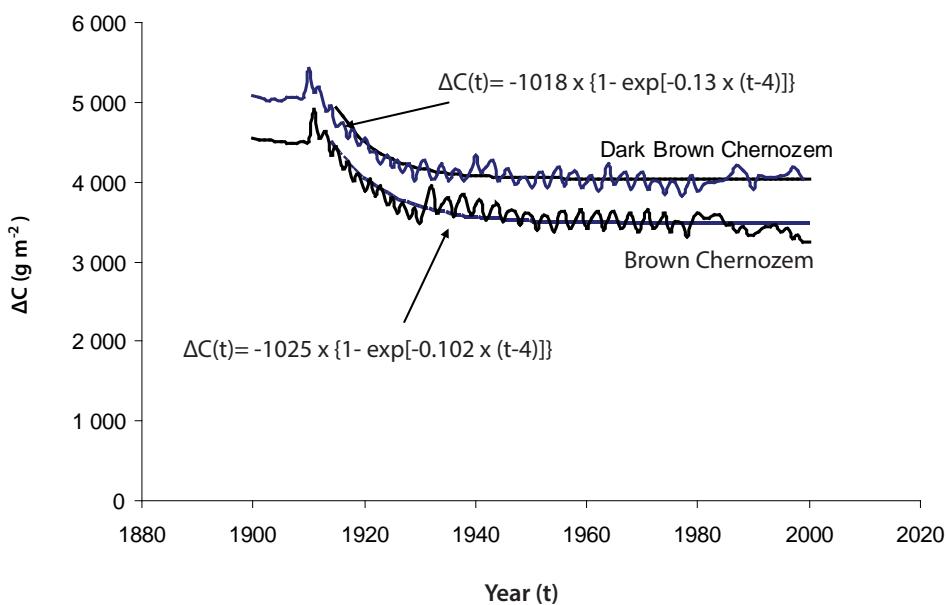
Thus, the total losses of SOC in grassland converted to cropland were calculated using an IPCC Tier 2 approach:

Equation A3.5–15

$$\Delta C_{GLCL} = \sum_{1951-n} \sum_{ALL SLC} \sum_t (\Delta C_t \times AREA_{GLCL})$$

ΔC_{GLCL}	=	losses of SOC in the inventory year n due to conversion of grassland to cropland since 1951 until year n, Mg C
$ALL SLC$	=	all soil polygons that contain grassland conversion to cropland
t	=	time after grassland conversion, years
ΔC_t	=	change in SOC for the t th year after conversion, Mg C ha ⁻¹
$AREA_{GLCL}$	=	area of grassland converted to cropland annually since 1951, ha

Figure A3.5–17 Century-Simulated SOC Dynamics after Breaking Grassland to Cropland for Brown and Dark Brown Chernozemic Soils



Losses of Soil Organic N and N₂O Emissions

Change in SON is estimated as a fixed proportion of C losses. Where changes in both SON and SOC were determined, the average change in SON was 0.06 kg N lost/kg C lost (McConkey et al., 2007a). Thus, the emissions of N₂O in grassland converted to cropland were calculated using an IPCC Tier 2 approach:

Equation A3.5-16

$$N_2O_{GLCL} = \sum_{1951-n} \sum_{ALLSLC} \sum_t (\Delta C_{GLCL} \times AREA_{GLCL}) \times 0.06 \times EF_{Base} \times RF_SN \times RF_TX \times RF_NSE \times \frac{44}{28}$$

N_2O_{GLCL}	=	emissions of N ₂ O in the year n due to the conversion of grassland to cropland since 1951 until year n, kt
$ALLSLC$	=	all soil polygons that contain grassland conversion to cropland
t	=	time after grassland conversion, years
ΔC_{GLCL}	=	change in SOC for the t th year after grassland conversion, Mg C ha ⁻¹
$AREA_{GLCL}$	=	area of grassland converted to cropland annually since 1951, ha
EF_{Base}	=	N ₂ O emission factor, defined as a function of long-term climate normals (growing season precipitation from May to October at an ecodistrict level (see section A3.4.5))
RF_SN	=	ratio factor for adjusting source of N on soil N ₂ O emissions (see section A3.4.5)
RF_TX	=	ratio factor for adjusting soil texture (TX) effect on soil N ₂ O emissions (see section A3.4.5)
RF_NSE	=	ratio factor for correcting non-growing season soil N ₂ O emissions (see section A3.4.5)
0.06		ratio of SON to SOC losses
$44/28$		coefficient converting N ₂ O-N to N ₂ O

Data Sources

The area of grassland reported in the category Grassland Remaining Grassland was estimated using a combination of data from the *Census of Agriculture* and EO data. Area estimates reported in the category Grassland Converted to Cropland were based on reconciling changes in land area between Grassland Remaining Grassland and land in cropland management. To avoid issues associated with farm headquarters reporting, data were aggregated to the ecodistrict level prior to the land reconciliation process. Ecodistrict estimates of area of grassland converted to cropland were then apportioned back to SLC polygons.

Within an SLC, areas under Grassland Remaining Grassland were allocated to soil components identified as “low” for “likelihood of being cropped.” Soil C data from the National Soil Database were used to calculate an average SOC content for soils within the SLC polygon.

Uncertainty

The conversion of agricultural grassland to cropland occurs, but the reverse does not. The uncertainty of the area of this conversion in a given ecodistrict cannot be larger than the uncertainty of the final area of cropland or the initial area of grassland. Therefore, the uncertainty of the area of conversion was set to the lower of the uncertainty of the area of land in the Cropland or Grassland category. The factor scaling coefficient was assumed to be the same as for annual-perennial crop conversions (McConkey et al., 2007b).

A3.5.4.3. Forest Land Converted to Cropland

Emissions of CO₂ and N₂O from Soils

Clearing forest to increase agricultural land is a declining but still significant practice in Canada. This section describes the methodology for estimating CO₂ and N₂O emissions associated with soil disturbance. The method for estimating emissions from biomass upon conversion is presented in sections A3.5.2.1 and A3.5.2.5. For SOC change, it is necessary to differentiate between Eastern and Western Canada.

Eastern Canada

There are many observations that compare SOC for land under forest with SOC for adjacent land under agriculture in Eastern Canada. The mean loss of C was 20.3% for a depth of approximately 30 cm (McConkey et al., 2007a). This value is comparable to that found in the soil database in CanSIS (Table A3.5–10), indicating that, on average, SOC for the uppermost 30 cm of soil under agriculture was 20.5% less than that of soil under forest.

Although the SOC for forested land accounts for C in the litter layer above mineral soil, in practice there is always uncertainty in quantifying the litter layer C and organic C within soil debris (Paul et al., 2002). Soil erosion, which is generally assumed to increase under agriculture, also reduces measured SOC on agricultural land.

The Century model (version 4.0) was used to estimate the SOC dynamics from forest conversion (Figure A3.5–18). In the first years after conversion, there is an increase in soil organic matter, as litter and above-ground and below-ground DOM become part of SOC. After a few years, SOC falls below the amount that existed before forest conversion. The rate of SOC decline gradually decreases with time.

The following equation was fit to the Century results in Figure A3.5–17, neglecting the initial SOC increase:

Equation A3.5–17

$$\Delta C(t) = \Delta C_{Dmax} \times [1 - \exp\{-k \times (t - t_{lag})\}]$$

$\Delta C(t)$	=	change in SOC for the t th year after conversion, Mg C ha ⁻¹
ΔC_{Dmax}	=	maximum change in SOC from forest conversion to agriculture, Mg C ha ⁻¹
k	=	rate constant for describing the decomposition, yr ⁻¹
t	=	time since conversion of forest land, years
t_{lag}	=	time lag before ΔC becomes negative, years

In the case of simulated SOC after conversion of deciduous forest to cropland (Figure A3.5–19), 25% of C losses occur within 20 years of forest conversion and 90% within 100 years. Given the uncertainty of actual dynamics, it was assumed that there is no time lag in SOC loss from forest conversion, so that SOC starts to decline immediately upon forest conversion, i.e., the fitted SOC loss (Figure A3.5–14) is used to estimate SOC loss with time lag set to 0 after fitting.

The mean loss of 20.5% of SOC resulting from forest conversion to cropland for Eastern Canada, based on CanSIS information, was assumed to correspond to approximately 100 years after forest conversion. The ΔC_{Dmax} is therefore corrected by a factor of 1/0.927, where it is assumed that only 92.7% of the C has been lost after 100 years, based on the integration of Equation A3.5–18, resulting in a ΔC_{Dmax} value of 22.1% of SOC under long-term forest. As the CanSIS soil database has more data on SOC for conditions under long-term cropland than on SOC under long-term forest in areas where cropland exists, the maximal SOC losses were calculated relative to stabilized cropland SOC (i.e., loss = 0.221/(1–0.221) × SOC or loss = 0.284 × SOC under agriculture). Therefore, the final equation for estimating SOC loss for forest conversion to cropland in Eastern Canada is:

Equation A3.5–18

$$\Delta C(t) = 0.284 \times SOC_{agric} \times [1 - \exp(-0.0262 \times t)]$$

$\Delta C(t)$	=	change in SOC for the t th year after conversion, Mg C ha ⁻¹
SOC_{agric}	=	0- to 30-cm SOC from CanSIS for a cropland soil, Mg C ha ⁻¹
-0.0262	=	rate constant for describing the decomposition, yr ⁻¹
t	=	time since conversion, years

Thus, the total amount of SOC lost from forest land converted to cropland is estimated using the following equation:

Equation A3.5–19

$$\Delta C_{FLCL} = \sum_{1970-n} \sum_{ALLSLC} \sum_t (\Delta C_t \times AREA_{FLCL})$$

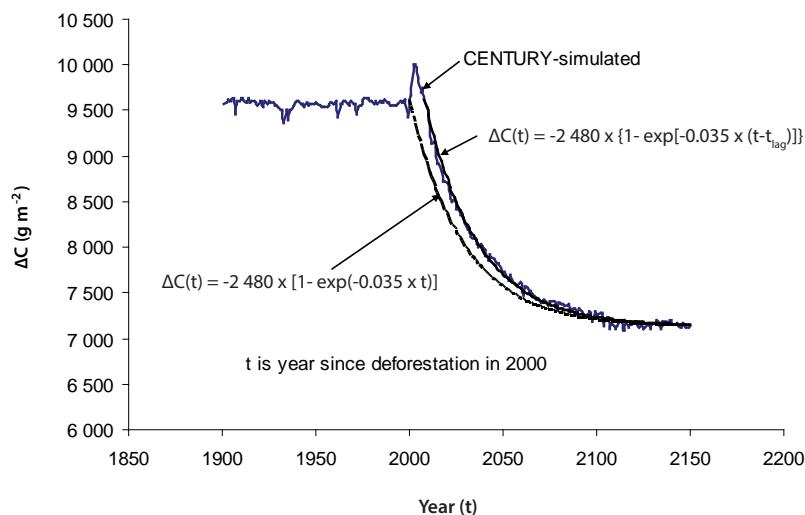
ΔC_{FLCL}	=	total SOC loss in year n from the conversion of forest land to cropland since 1970 until year n, Mg C ha ⁻¹
t	=	time after the conversion, year
$ALLSLC$	=	all soil polygons that contain forest land converted to cropland
ΔC_t	=	change in SOC for the t th year after conversion, Mg C ha ⁻¹ (see Equation A3.5–18)
$AREA_{FLCL}$	=	area of forest land converted to cropland annually since 1970, ha

Note that the SOC loss predicted by Equation A3.5–19 is in addition to C stock changes in tree biomass and woody DOM that existed in the forest at the time of forest conversion.

Table A3.5–10 **Soil Organic C for Forested and Agricultural Land in Eastern and Western Canada from the Canadian Soil Information System Database (0- to 30-cm soil depth)**

Soil Texture	Soil Organic Carbon (Mg C ha ⁻¹)		Difference (%)
	Forested Land ^a	Cropland ^a	
Eastern Canada			
Coarse	85 (26)	68 (42)	-20
Medium	99 (38)	77 (35)	-22
Fine	99 (58)	78 (36)	-21
Western Canada			
Coarse	73 (39)	74 (38)	0
Medium	66 (30)	73 (30)	4
Fine	74 (38)	77 (25)	1
Note:			
a. Standard deviation in parentheses.			

Figure A3.5–18 **Century-Simulated Soil Organic Carbon Following Conversion of Deciduous Forest to Cropland**



Based on the field observations, average N change in Eastern Canada was -5.2%, representing 0.4 Mg N ha⁻¹ (McConkey et al., 2007a). For those comparisons where both N and C losses were determined, the corresponding C loss was 19.9 Mg C ha⁻¹, and C loss was 50 times N loss. For simplicity, it was assumed that N loss was a constant 2% of C loss. Thus, N₂O emissions from the conversion of forest land to cropland are estimated using the following equation:

Equation A3.5–20

$$N_2O_{FLCL} = \sum_{1970-n} \sum_{ALLSLC} \sum_t (\Delta C_t \times AREA_{FLCL}) \times 0.02 \times RF_{Base} \times RF_{SN} \times RF_{TX} \times RF_{NSE} \times \frac{44}{28} \times 1000^{-1}$$

N_2O_{FLCL}	=	emissions of N ₂ O subject to conversion of forest to cropland since 1970 until year n (latest inventory year), kt
$ALL SLC$	=	all soil polygons that contain forest land conversion
ΔC_t	=	change in SOC for the t th year after conversion, Mg C ha ⁻¹ yr ⁻¹
$AREA_{FLCL}$	=	area of forest land converted to cropland annually since 1970, ha
0.02	=	conversion of C to N
RF_{Base}	=	base emission factor, defined as a function of long-term climate normals (growing season precipitation from May to October at an ecodistrict level (see section A3.4.5))
RF_{SN}	=	ratio factor for adjusting source of N on soil N ₂ O emissions (see section A3.4.5)
RF_{TX}	=	ratio factor for adjusting soil texture (TX) effect on soil N ₂ O emissions (see section A3.4.5)
RF_{NSE}	=	ratio factor for correcting non-growing season soil N ₂ O emissions (see section A3.4.5)
t	=	time after the conversion, year
$44/28$	=	coefficient converting N ₂ O-N to N ₂ O
1000^{-1}	=	Converting from Mg to kt

Western Canada

Much of the current agricultural soil in Western Canada was grassland prior to cultivation. Hence, forest conversion has involved primarily forest that adjoins grassland areas. There is also limited conversion of secondary forest that has grown on former grassland since the suppression of wildfires with agricultural development. Historically, forest conversion has been less important in Western Canada than in Eastern Canada, and fewer comparisons of SOC under forest and agriculture are available in the literature. Ellert and Bettany (1995) reported that there was no difference in SOC between native aspen forest and long-term pasture that remained uncultivated since clearing for an Orthic Gray Luvisol near Star City, Saskatchewan.

The CanSIS data provide numerous comparisons of SOC under forest with that under cropland (Table A3.5–10). On average, these data indicate that there is no loss of SOC from forest conversion. This suggests that, in the long term, the balance between C input and SOC mineralization remains similar under agriculture to what it was under forest. It is important to recognize that the northern fringe of western Canadian agricultural areas, where most forest conversion is now occurring, is marginal for annual crops, and pasture and forage crops are the primary agricultural uses after clearing. In general, C loss from forest conversion to agriculture is lowest where agricultural land contains forages and pastures.

For Western Canada, no loss of SOC over the long term was assumed from forest conversion to pasture and forage crops. Therefore, the C loss from land conversion in Western Canada would be from losses of C in above-ground and below-ground tree biomass and coarse woody DOM that existed in the forest at the time of conversion. Similarly, average organic N change in Western Canada for sites at least 50 years from breaking was +52% (McConkey et al., 2007a), reflecting substantial added N in agricultural systems compared with forests. However, recognizing the uncertainty about actual soil C–N dynamics upon conversion, forest land converted to cropland was assumed not to be a source of N₂O from the soil pool. N₂O emissions are reported wherever biomass burning occurs during conversion (see section A3.5.2.1).

Data Sources

The approach used to estimate the area converted from forest to cropland is described in section A3.5.2.5. The annual forest conversion by RU was disaggregated to SLC polygons on the basis of concurrent changes in the area of cropland within SLC polygons. Only polygons that showed an increase in cropland area for the appropriate time period were allocated to forest conversion, and the amount allocated was equivalent to that polygon's proportion of the total cropland increase within the RU.

Uncertainty

The uncertainty of C change in each reporting zone was estimated differently for Eastern and Western Canada because of differences in C change estimation methods (McConkey et al., 2007b). For Western Canada, an uncertainty of C change was estimated, although the mean value of SOC change factor was 0. The assumption was that the uncertainty of SOC change after forest land to cropland conversion in Western Canada would follow a similar pattern as that for Eastern Canada.

A3.5.5. **Grassland**

Land in the agricultural Grassland category is defined as unimproved pasture used for grazing domestic livestock, but only in geographical areas where grassland would not naturally grow into forest if abandoned, i.e., southern Saskatchewan and Alberta and a small area of southern British Columbia. These grasslands developed under millennia of grazing by large animals, such as bison, and periodic burning. Essentially, the agricultural Grassland category consists of extensively managed native range in Canada.

The primary direct human activities on agricultural grassland in Canada are fire suppression; seeding new plant species into the grassland; and adjusting the amount, duration and timing of grazing by domestic livestock. Methodologies for estimating emissions or removals of CO₂ as a result of direct human activities and for estimating CH₄ and N₂O emissions from natural or prescribed fires on agricultural grassland in Canada are presented in the following section.

A3.5.5.1. **Grassland Remaining Grassland**

The development of the CO₂ estimate method is based on the premise that on long-existing managed grassland, changes in soil C stocks over time occur following changes in soil management that influence the rates of either C additions to or C losses from the soil.

Equation A3.5–21

$$SOC = SOC_{REF} \times F_{MG} \times F_I$$

SOC	=	soil organic C stock at any particular time since management and input change, Mg C ha ⁻¹
SOC_{REF}	=	the reference SOC stock, Mg C ha ⁻¹
F_{MG}	=	C stock change factor for management regime, dimensionless
F_I	=	C stock change factor for input of organic matter, dimensionless

The total area of managed grassland is calculated as follows:

Equation A3.5–22

$$A_n = GLGL_{1990} - \sum_{1990}^n GLCL$$

A_n	=	the total area of grassland remaining grassland in the inventory year n, ha
$GLGL_{1990}$	=	the area of grassland remaining grassland in 1990, ha
$GLCL$	=	the area of grassland converted to cropland since 1990, ha

Therefore, the net change in SOC because of management and input changes from grassland remaining grassland can be estimated using the IPCC tier-1 method as follows:

Equation A3.5–23

$$\Delta C_{GGMineral} = [(SOC_0 - SOC_{0-T}) \times A] / t$$

$\Delta C_{GGMineral}$	=	the net change in SOC due to management and input from grassland remaining grassland, Mg C ha ⁻¹ yr ⁻¹
SOC_0	=	SOC stock in the inventory year, Mg C ha ⁻¹
SOC_{0-T}	=	SOC stock T years prior to the inventory year, Mg C ha ⁻¹
A	=	area of change in management and input from grassland remaining grassland, ha
t	=	inventory time period, years (default 20 years)

If no change in management practices or input occurs, the C stocks are assumed to be at equilibrium, and the change in C stocks is therefore deemed to be zero.

There are a number of studies on the effects of grazing versus no grazing on SOC. Although the productivity of heavily grazed pasture is lower, which may lead to a decline in range conditions, this was not related to declines in SOC (Biondini and Manske, 1996). The effect of grazing regime is complex, because of the effects of grazing on plant community as well as effects on C input to soil from both above-ground and below-ground plant growth (Schuman et al., 2002; Liebig et al., 2005). An additional influence of grazing regime is the increased return of C in fecal matter as stocking rate increases (Baron et al., 2002). Bruce et al. (1999) estimated that there was no opportunity to increase SOC from grazing management improvements on extensively managed rangeland in North America.

The addition of organic amendments and inorganic fertilizer will increase the productivity of native grassland (Smoliak, 1965), suggesting that these practices could increase SOC through greater C inputs. However, such practices are basically of academic interest, as the only economically practical management options for semi-arid grasslands are altering grazing regime, burning, and introducing new plant species (Liebig et al., 2005).

Grasslands managed for grazing in Western Canada in the Brown and Dark Brown soil zones of Alberta, Saskatchewan and British Columbia are occasionally burned by wildfire and by prescribed burning for purposes such as brush management, habitat management, the removal of decadent vegetation, and military training exercises. Burning from managed grassland is a net source of CH₄, CO, NO_x and N₂O.

Equation A3.5–24

$$EMISSION_{BURN} = \sum (AREA_i \times FUELLOAD_i \times C_{E,i} \times G_{EF}) / 1000$$

$EMISSION_{BURN}$	=	emissions of CH ₄ or N ₂ O from prescribed and non-prescribed burning of managed agricultural grassland, kt CH ₄ or N ₂ O
$AREA_i$	=	area of the i th managed agricultural grassland subject to burning, ha
$FUELLOAD_i$	=	average fuel load for the i th managed agricultural grassland subject to burning, Mg DM (dry matter) ha ⁻¹
$C_{E,i}$	=	combustion efficiency for the i th managed agricultural grassland subject to burning, fraction, dimensionless
G_{EF}	=	emission factor of CH ₄ (2.7 g CH ₄ kg ⁻¹ dry matter burnt) or N ₂ O (0.07 g N ₂ O kg ⁻¹ dry matter burnt) (IPCC, 2006)
1000	=	conversion of Mg to kt

Data Sources

As discussed in the section Grassland Converted to Cropland, the area reported for the subcategory Grassland Remaining Grassland was estimated using a combination of data from the *Census of Agriculture* and EO, as described in section A3.5.4.1. There are no detailed comprehensive activity data over time on management change for Canadian agricultural grassland, except for wild and prescribed fires. Activity data on area, fuel load and combustion efficiency for each burning event for managed agricultural grassland were collected through consultations (Bailey and Liang, 2013). Activity data from 2013 to 2015 were updated in 2017 and were kept constant after the sampling period.

A3.5.6. Wetlands

A3.5.6.1. Peat Extraction

General Approach and Methods

Peat extraction in Canada is for the production of horticultural peat products and related applications, and not for use as fuel. Since the 1970s, the vacuum harvesting technique has been the dominant method of peat extraction. This technique requires an extensive network of drainage ditches to dry the peat for harvesting by heavy vacuum harvesters. Prior to the implementation of vacuum harvesting, manual block-cutting was used to extract peat blocks with shovels, resulting in topography of high baulks and low trenches. Although these manual methods are no longer used, numerous abandoned block-cut sites remain in the landscape.

Emissions of CO₂, CH₄ and N₂O were estimated for the conversion and management of peatlands for peat extraction using an IPCC Tier 2 method in accordance with guidance from a combination of the 2006 IPCC Guidelines and the 2013 IPCC Wetlands Supplement (IPCC, 2014). The approach is based on domestic science and land management practices specific to peat extraction activity in Canada. Emission estimates include on-site CO₂, CH₄ and N₂O emissions, off-site CO₂ emissions from extracted peat, and waterborne C losses of dissolved organic carbon (DOC) from drained and rewetted sites.

Domestic GHG flux studies at peat extraction sites in Canada were reviewed and measurements compiled to develop country-specific emission factors and parameters (Table A3.5–11). As the majority of flux measurements were reported for the growing season, annual CO₂ emission factors were developed by adding measured winter values from Strack and Zuback (2013), consistent with drained peatlands having higher winter CO₂ emissions than natural peatlands. Annual CH₄ emission factors were developed assuming that non-growing season fluxes are 15% of annual totals based on natural peatland sites (Saarnio et al., 2007).

Table A3.5–11 Parameters and Emission Factors for Estimating Emissions from Peat Extraction

Emission Factor/Parameter	Unit	Value	Sources
Biomass Clearing			
Forest land biomass cleared	t C ha ⁻¹	19.2	Hayne and Verbicki, 2011
Other land biomass cleared	t C ha ⁻¹	2.8	Hayne and Verbicki, 2011
Drainage			
CO ₂ from drained areas	t CO ₂ ha ⁻¹ yr ⁻¹	11.4	Moore et al., 2002, as cited in Cleary, 2003; Glatzel et al., 2003; Waddington et al., 2010; Strack and Zuback, 2013; Strack et al., 2014
CO ₂ -DOC from drained areas	t CO ₂ ha ⁻¹ yr ⁻¹	0.60	Waddington et al., 2008; Strack and Zuback, 2013
CH ₄ from drained fields	t CH ₄ ha ⁻¹ yr ⁻¹	0.008	Moore et al., 2002 as cited in Cleary, 2003; Waddington and Day, 2007; Strack and Zuback, 2013; Strack et al., 2014
CH ₄ from drainage ditches	t CH ₄ ha ⁻¹ yr ⁻¹	0.15	Waddington and Day, 2007
N ₂ O from drained areas	t N ₂ O ha ⁻¹ yr ⁻¹	0.00047	IPCC, 2014 (Table 2.5, Default value for Boreal & Temperate climate zone)
CO ₂ from abandoned block-cut areas	t CO ₂ ha ⁻¹ yr ⁻¹	8.6	Waddington and Price, 2000; Waddington and Warner, 2001; Waddington et al., 2002; McNeil and Waddington, 2003
CH ₄ from abandoned block-cut areas	t CH ₄ ha ⁻¹ yr ⁻¹	0.012	Waddington and Price, 2000
CO ₂ tree plantation biomass uptake	t CO ₂ ha ⁻¹ yr ⁻¹	-0.32	Garcia Bravo, 2015
Peat Stockpiling and Product Production			
Amount of stockpiled peat	t C ha ⁻¹	50	Cleary, 2003
Exponential decay constant, stockpiled peat		0.05	Cleary, 2003
Carbon fraction of peat products	t C t air-dry peat ⁻¹	0.26	Hayne et al., 2014
Rewetting and Restoration			
CO ₂ from restored areas	t CO ₂ ha ⁻¹ yr ⁻¹	7.60	Moore et al., 2002 as cited in Cleary, 2003; Petrone et al., 2001; Petrone et al., 2003; Waddington et al., 2010; Strack and Zuback, 2013; Strack et al., 2014
CO ₂ -DOC from restored areas	t CO ₂ ha ⁻¹ yr ⁻¹	0.13	Waddington et al., 2008; Strack and Zuback, 2013
CH ₄ from restored fields	t CH ₄ ha ⁻¹ yr ⁻¹	0.03	Moore et al., 2002 as cited in Cleary, 2003; Waddington and Day, 2007; Strack and Zuback, 2013; Strack et al., 2014
CH ₄ from restored ditches	t CH ₄ ha ⁻¹ yr ⁻¹	0.28	Waddington and Day, 2007; Strack and Zuback, 2013
N ₂ O from restored areas	t N ₂ O ha ⁻¹ yr ⁻¹	N/A	IPCC, 2014, Default assumption of no N ₂ O emissions from rewetted/restored areas

Note: All values where the greenhouse gas (GHG) is specified use units of the relevant GHG (CO₂, CH₄ or N₂O) instead of carbon (C) or nitrogen (N).

Owing to the extraction technology and desired properties of sphagnum peat, preference with respect to site selection is given to open bog (nutrient poor – ombrotrophic) peatlands, which are classified as Other Land under Canada's land categorization framework for the LULUCF sector described in section 6.2 of Chapter 6. Therefore, only approximately 5% of pre-conversion area meets the definition of the Forest Land category. Emission estimates are separated into the subcategories Land Converted to Peat Extraction and Peat Extraction Remaining Peat Extraction. In calculating emissions from land conversion, a land-use change period of one year is used to represent the land conversion practices of draining and clearing the surface vegetation layer (acrotelm) in preparation for peat extraction. Subsequently, emissions from the ongoing management of peat extraction sites, as well as their decommissioning through abandonment, rehabilitation, or rewetting and restoration, are all reported under the subcategory Peat Extraction Remaining Peat Extraction. The following sections describe the sources of GHG emissions and removals through the peat extraction land management phases.

Biomass Clearing and Drainage

At extraction sites, vegetation removal and drainage result in a loss of CO₂ uptake, enhanced peat decomposition, and DOC export resulting in increased CO₂ emissions. Emissions of CH₄ decrease substantially from drained fields, but drainage ditches, which occupy 5% of the drained area, become CH₄ hot spots (Waddington and Day, 2007). Enhanced peat decomposition also increases N₂O emissions. CO₂ and CH₄ emission factors for drained areas were derived from domestic studies (Table A3.5–11), but due to a lack of domestic N₂O measurements, the default emission factor for peat extraction sites from the 2013 IPCC Wetlands Supplement (IPCC, 2014) was used.

Sites that are no longer economical for extraction are decommissioned or abandoned. The altered hydrology and peat properties of these sites hinder natural regeneration, resulting in persistent CO₂ emissions (Waddington et al., 2002). However, revegetation occurs more frequently at abandoned block-cut sites in comparison to vacuum-mined sites, although total vegetation coverage is low and moss regeneration is limited to wetter trench depressions (Poulin et al., 2005). The CO₂ emission factor for abandoned block-cut areas is lower than for areas drained for vacuum harvesting, while the CH₄ emission factor is higher, likely due to greater revegetation and wetter conditions at block-cut sites.

At some abandoned sites, rehabilitation measures are undertaken to establish another type of environment. Given the lack of flux measurements for these sites, the emission factors for drained areas are generally used for rehabilitated areas. However, the uptake of CO₂ by trees in tree plantations is calculated on the basis of measurements at a tree plantation study (Garcia Bravo, 2015). Tree plantations may increase CO₂ sequestration in tree biomass, but this does not offset the large CO₂ emissions from drained peat.

Peat Stockpiling and Product Production

Harvested peat is left in stockpiles before being processed into various peat products. Emissions from peat stockpiles are calculated as an exponential decay for half a year (Cleary et al., 2005). Once it is packaged into products, Canadian peat is transported off-site, largely to the United States, for non-energy uses such as horticulture, where it is assumed to decay in an aerobic environment. Due to the lack of information on decay rates by end use, it is assumed that all the carbon in the peat is emitted in the extraction year. Emissions of CO₂ are calculated based on an estimate of total organic C in the peat using a country-specific C fraction parameter (Table A3.5–11) derived from laboratory analysis of pure peat products with moisture contents ranging from 27% to 64% (Hayne et al., 2014).

Rewetting and Restoration

An increasing number of decommissioned sites are rewetted and restored. Rewetting practices increase anaerobic conditions, which reduce peat decay and DOC export, thereby decreasing CO₂ emissions while increasing CH₄ emissions (Strack and Zuback, 2013). Since the 1990s, the moss layer transfer technique has been used in Canada for the restoration of peatlands dominated by *Sphagnum* mosses with the aim of restoring sites to peat-accumulating ecosystems. This technique consists of rewetting and sowing fields with fresh moss spores and spreading a layer of straw mulch to support moss regeneration (Rochefort et al., 2003). Long-term monitoring of restoration sites indicates that rewetting and restoration success varies due to management (e.g., effectiveness of blocking secondary drainage network, timing of restoration procedures and quality of plant material spread) and weather conditions post-restoration (González and Rochefort, 2014). Domestic GHG research at sites restored for 10 years or less has shown that there is high variability among sites ranging from sources to sinks. Given the range of success among sites and the variability in flux measurements, average emission values are used to best represent the net flux of rewetted and restored sites.

Data Sources

An EO mapping approach based on manual delineation and interpretation of aerial photography, satellite imagery and ancillary data was developed to map the extent of peatland areas disturbed by peat extraction for circa 1990, 2007 and 2013 time periods. Through image interpretation, the total disturbed area was allocated into the following four land management subcategories: active extraction areas, abandoned areas, rehabilitated areas, and restored areas. Geospatial

A
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data developed by the Peatland Ecology Research Group and information provided by industry experts were utilized to aid subcategory allocation. In addition, for a subset of sites, the pre-disturbance land cover class (forest, shrubby or open bog peatland) was determined in order to identify the land category types converted (Forest Land or Other Land).

Annual area estimates were developed using interpolation between mapped time periods and extrapolation after 2013. Annual area estimates for various land management categories were then refined based on secondary data sources. The two main secondary data sources were industry statistics on peatland areas managed for peat extraction in 2015 compiled by the Canadian Sphagnum Peat Moss Association (CSPMA) and a survey of abandoned peat extraction sites in the provinces of Quebec and New Brunswick (Poulin et al., 2005). Secondary data sources were used to provide a comparative check of total areas converted to peat extraction historically and current production areas, and to complement limitations in the ability of the mapping approach to identify land management subcategories. National peat production statistics were used to represent the annual amount of extracted peat transported off site (NRCan, 2020).

Uncertainty

Given the increased availability and quality of EO imagery and ancillary information over time, it is assumed that there is a decrease in uncertainty in the mapped areas for the later mapping periods. The use of high-resolution satellite imagery for the 2013 time period reduced uncertainty in the overall estimate of the total areas converted for peat extraction. However, there is considerable uncertainty associated with identifying land management subcategories. Uncertainty in the 2015 CSPMA industry statistics is associated with different interpretations of land management category definitions (e.g., restoration) and incomplete coverage of lands not managed by industry association members.

There is a lack of domestic GHG measurements for the various categories of decommissioned sites. Therefore, emission factors may not represent the full range and success rates of applied rehabilitation and restoration techniques. The large variation in moisture content among peat products may contribute substantially to the uncertainty of off-site CO₂ emission estimates from extracted peat.

A3.5.6.2. Flooded Land

General Approach and Methods

Following the 2006 IPCC Guidelines, emissions reported under the category Land Converted to Flooded Land (creation of flooded lands, namely reservoirs) are estimated for all known reservoirs flooded for 10 years or less. Only CO₂ emissions are reported. An IPCC Tier 2 method was used, whereby country-specific CO₂ emission factors were developed based on measurements, as described below (Blain et al., 2014). It is believed that the default approach, assuming that all biomass C would be emitted upon flooding, would overestimate immediate forest conversion emissions from reservoir creation, because the majority of submerged forest biomass does not decay for an extended period of time.

Two complementary estimation methodologies are used to account for GHG fluxes from flooded lands, depending on land conversion practices. When there is evidence of forest clearing and/or burning prior to flooding, immediate and residual emissions from all forest C pools are estimated with the CBM-CFS3 (see section A3.5.2.1). Emissions from forest clearing for infrastructure development are reported under the subcategory Forest Land Converted to Settlements. Emissions resulting from the use and disposal of wood products that are harvested before flooding are reported under the category Harvested Wood Products (see section A3.5.3).

In the absence of evidence of forest clearing, it was assumed that all vegetation was simply flooded, leading to the emission—as CO₂—of a fraction of the submerged C from the surface of the reservoir. The proportion of the area flooded that was previously forested was used to attribute these emissions to either the Forest Land Converted to Flooded Land category or the Other Land Converted to Flooded Land category.

Since 1993, measurements of CO₂ fluxes have been made above some 57 hydroelectric reservoirs in four provinces: Quebec, Manitoba, British Columbia, and Newfoundland and Labrador (Duchemin, 2006). In most studies, the reservoirs were located in watersheds little affected by human activities, with the notable exception of Manitoba. In almost all cases, only diffusive fluxes of CO₂, CH₄ or N₂O (in order of frequency) were measured. Studies on ebullition, degassing emissions and winter emissions are rare and insufficient to support the development of domestic emission factors. Measurements of diffusive fluxes above the surface of reservoirs were compiled for the entire country. Out of these measured reservoirs, a subset of 25 was selected to develop a national emission curve for the 50-year period following impoundment. These measurements were selected based on the availability of documentation of measurement procedures and measurement comparability. The emission curve was developed from 25 reservoirs and a total of 34 measurements (Figure A3.5–19). It is important to note that each of these measurements (data points in Figure A3.5–19) represents, on average, the integration of between 8 and 28 flux samples per reservoir. Non-linear regression analysis was used to parameterize the emission curve.

Equation A3.5–25

$$CO_2 \text{ rate } L_{\text{reservoir}} = b_0 + b_1 \times \ln(t)$$

$CO_2 \text{ rate } L_{\text{reservoir}}$	=	rate of CO_2 emissions from land converted to flooded land (reservoirs), mg m^{-2} per day
b_0	=	curve parameters, dimensionless
t	=	time since flooding, years

Total CO_2 emissions from the surface of reservoirs were estimated as the sum of all emissions from reservoirs flooded for 10 years or less:

Equation A3.5–26

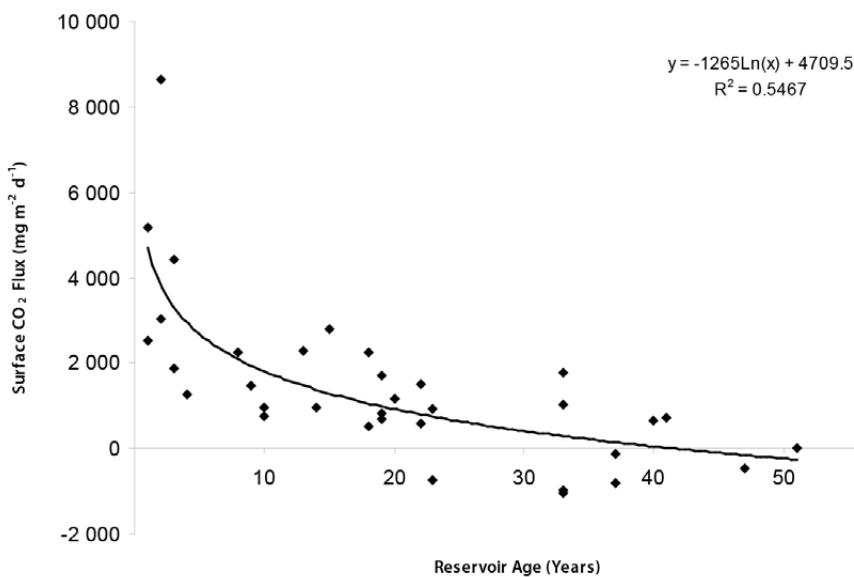
$$CO_2 \text{ L}_{\text{reservoirs}} = \sum(CO_2 \text{ rate } L_{\text{reservoir}} \times A_{\text{reservoir}} \times Days_{\text{ice free}} \times 10^{-8})$$

$CO_2 \text{ L}_{\text{reservoirs}}$	=	emissions from lands converted to flooded land (reservoirs), $\text{Gg CO}_2 \text{ yr}^{-1}$
$CO_2 \text{ rate } L_{\text{reservoir}}$	=	rate of CO_2 emissions for each reservoir, mg m^{-2} per day
$A_{\text{reservoir}}$	=	reservoir area, ha
$Days_{\text{ice free}}$	=	number of days without ice, days
10^{-8}	=	conversion factor from mg to Gg

Reservoir area was used as the best available estimate of the area converted to managed flooded lands (reservoirs) although, in reality, reservoirs may contain islands, i.e., emergent land areas. “Ice-free period” was defined as the average number of days between the observed freeze date and the breakup date of ice cover on a body of water (Magnuson et al., 2000). In the case of hydroelectric reservoirs, locations were mapped and estimates of the ice-free period were generated from the Lakes – Ice-Free Period isoline map of Canada (NRCan, 1974).

Emissions were calculated starting on the year of flooding completion. Reservoirs take a minimum of one year to fill following dam completion, unless otherwise confirmed. As CO_2 emissions from the surface of reservoirs are reported only for the 10 years following impoundment, all flooding events since 1980 were used.

Figure A3.5–19 Logarithmic Curve Fit for National Reservoir Emission Factors



Data Sources

The three main data sources used to develop area estimates were information on forest conversion due to reservoir impoundment in reporting zones 4 (Taiga Shield East) and 5 (Boreal Shield East) (see section A3.5.2.5), the Canadian Reservoir Database (Duchemin, 2002), and official industry numbers derived from industry correspondence³⁹ (Eichel, 2006).

The Canadian Reservoir Database contains records of 282 hydro reservoirs. Information from provincial and private hydroelectric utilities was accessed to update the database and cross-check the date of reservoir construction and the total reservoir area for all these reservoirs. In some instances, the database reported as new facilities some small, refurbished hydroelectric generation sites in the province of Quebec that entered into production under new ownership. As a result, a separate category was added to the database to document both the original construction and commissioning of a dam and the date when a hydroelectric facility was refurbished without any changes to the reservoir area.

It is important to note that fluctuations in the area of Land Converted to Flooded Land (reservoirs) reported in the CRF tables are not indicative of changes in current conversion rates, but reflect the difference between land areas recently converted (less than 10 years ago) to reservoirs and older reservoirs (more than 10 years old), whose areas are thus transferred out of the accounting. The reporting system does not encompass all reservoir areas in Canada, which are monitored separately in the Canadian Reservoir Database.

Uncertainty

A temporal curve better reflects the decreasing trends of emission rates after impoundment than a unique emission factor. Hence, the domestic approach is believed to reduce the uncertainty in estimation factors. However, important sources of uncertainty still remain:

- **Seasonal variability** – Some reservoirs display marked seasonal variability in CO₂ fluxes, which are not taken into account in estimate development; anecdotal evidence suggests that algal bloom in the spring could be associated with this variability, especially in reservoirs subjected to anthropogenic nutrient inputs.
- **Reservoir area** – There are variations in reservoir area due to water level fluctuations during the year.
- **Emission pathways** – The omission of potentially important CO₂ emission pathways (e.g., degassing).

A3.5.7. Settlements

This category comprises estimates of removals of CO₂ from land classified as Settlements Remaining Settlements (C sinks in urban trees) and emissions from Land Converted to Settlements (conversion of forest land and of unmanaged grassland to Settlements). The following sections describe the approaches developed to estimate C sequestration by urban trees, emissions from the conversion of non-forest land (unmanaged grassland or tundra) to settlements in the Canadian Arctic and sub-Arctic and estimation of areas of conversion from cropland to settlements. Approaches, methods and data sources for estimating emissions from the conversion of forest land to settlements are covered in sections A3.5.2.1 and A3.5.2.5.

A3.5.7.1. Settlements Remaining Settlements

General Approach and Methods

In Canada, the management and monitoring of urban trees is done at the level of individual municipalities, and there is no centralized authority or organization with responsibility for compiling national-scale urban tree information. Taking into consideration the lack of specific species class information and the considerable resources it would require to develop such information, an approach based on urban tree crown (UTC) cover area was developed to estimate CO₂ sequestration by urban trees in Canada. The approach involves the sampling of digital air photos and high-resolution satellite imagery to estimate the proportion of UTC cover in Canada's major urban areas. The growth of urban trees in Canada was estimated using an IPCC Tier 2A approach (IPCC, 2006):

Equation A3.5-27

$$\Delta C_g = \sum AT \times CRW$$

ΔC_g	=	annual C accumulation attributed to biomass increment of urban trees in settlements remaining settlements, tonnes C yr ⁻¹
AT	=	total crown cover area of urban trees, ha
CRW	=	crown cover area-based growth rate for urban trees, tonnes C (ha ⁻¹ crown cover) yr ⁻¹

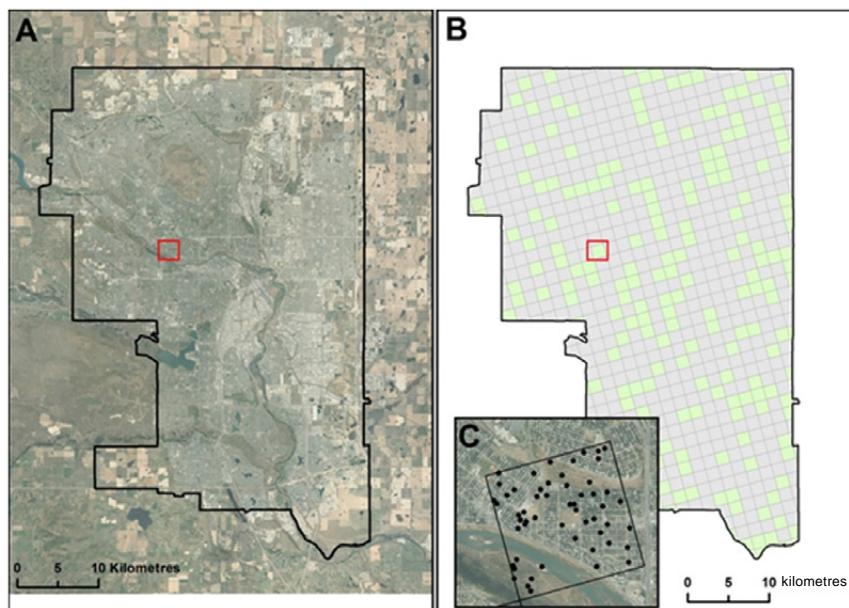
³⁹ Tremblay A, Hydro-Québec. 2010. Personal Communication Dated November 19, 2010, to Dominique Blain, Environment and Climate Change Canada.

The total urban area of Canada in 2012 was estimated using the boundaries of Statistics Canada's 2011 populated place digital boundary layer,⁴⁰ as it was the most nationally consistent delineation of urban areas available. The urban boundaries of 1990 were based on Statistics Canada 1990 polygon layer, but manually edited through visual interpretation of aerial photos and the 1990 GeoCover (MDA-Federal, 2004) ortho-rectified image data set, to reduce known over-bounding errors (Statistics Canada, 2010). The resulting 1990 urban layer represented a smaller total area (1.53 Mha) than the total urban area identified for 2012. Of the 947 population centres (2.42 Mha) in Canada, 69 (1.53 Mha) were extracted from the Statistics Canada data set that had populations greater than 30 000 individuals. This subset captured all major Canadian cities and represented 62% and 67% of the total urban area in 1990 and 2012, respectively. Furthermore, this subset holds the urban centres that represented approximately 79% and 76% of Canada's population in 1990 and 2012, respectively (Statistics Canada, 2011; McGovern and Pasher, 2016). While the population centres selected did not completely represent all populated places in Canada, many of the smaller communities that were filtered out are parts of an overall matrix of forest or agricultural land that may be captured under other land categories.

The 69 population centres were spatially allocated to 18 of the 60 RUs (see section A3.5.1). The 18 RUs encompassed 97% and 99% of the total area and population, respectively, of the total of 947 population centres. Estimates of the proportion of UTC cover were developed for each RU using a point-based sampling approach (Pasher et al., 2014). A grid cell approach was used to ensure good spatial distribution of sampling cells (Figure A3.5–20). Random points at a density of 55 points/km² on digital air photos or high-resolution satellite imagery were interpreted manually and classed into broad categories of tree crown or non-tree crown.

The same sampling point locations were used for both the 1990 and 2012 UTC assessments, although sampling cells and points which fell outside the 1990 urban boundary were not included in order to ensure that sampling was restricted so as to represent urban areas for that time period. A quality control process was implemented which involved random checks by alternative interpreters or reinterpretation. The percent UTC for each RU was calculated as the proportion of all points identified as tree canopy out of the total points that were assessed within the RU. The national-scale UTC estimate was 28.5% in 1990 and 27% in 2012.

Figure A3.5–20 Sampling Grids and Point Sampling over Georeferenced Air Photo



Note: Background imagery: (A) Calgary, Alberta urban area boundary, (B) 1 km × 1 km grid cells representing a 25% sampling rate with randomly selected grid cells shown in green, and (C) close-up of a single grid cell (20 pts km⁻² sampling). Orthophoto courtesy of City of Calgary.

⁴⁰ Statistics Canada. Populated Place spatial data and information available online at: <http://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2011-eng.cfm>.

The total crown cover area of urban trees for each RU was estimated by multiplying the % UTC by the total urban area estimates for the associated RU in 1990 and 2012. Although the urban area boundary has increased by 6% from 1990 to 2012, the national-scale estimate of crown cover changed little, with regional variation in trends. Gains in crown cover area (e.g., tree growth and planting) tended to balance with losses (e.g., tree removal, mortality and urban land-use change).

The crown cover area-based growth rate (CRW) values for the 18 RUs (see Table A3.5–12) are derived from assessments carried out in 16 Canadian cities using the same methodology used to develop CRW values for the United States. In RUs where cities were not assessed using that approach, values from proxy cities were used based on an ecologically similar Canadian RU, with the exception of RU 41, Pacific Maritime, for which the assessment for the U.S. city of Seattle was used (Steenberg et al., 2021). These assessments take into consideration the tree species, age and environmental conditions for each RU to determine gross sequestration rates. Net C sequestration was estimated as 74% of gross sequestration, accounting for urban tree growth characteristics and tree mortality and decomposition (Nowak et al., 2013). These growth and sequestration rates are applied to the 18 RUs and, as a result, estimates of UTC cover area and the sequestration rate are the main drivers of overall removal estimates. Interpolation and extrapolation were used to develop a consistent time series for the period 1990 to the latest inventory year.

Analysis of the fate of urban tree mortality (Tree Canada, 2019) suggested that approximately 13% of mortality in urban centres is used for firewood. As a result, the volume of firewood collected from urban trees was estimated by multiplying the C stocks for individual population centres by a 2.4% mortality rate of urban trees taken from (Tree Canada, 2018) and 13% of C from dead trees was assumed to be used as firewood (Tree Canada, 2019). The firewood supply was aggregated by RU and supplied a portion of the firewood demand estimated from consumption surveys described in section A3.5.3. To avoid double counting of emissions between the Settlements and Harvested Wood Products categories, the amount of C transferred to the HWP pool was attributed to the difference between the gross and net annual sequestration rates estimated by the i-Tree model. As a consequence the apparent C sink under the Settlements category is increased due to the combustion of this C as residential firewood being reported under Harvested Wood Products.

Uncertainty

The uncertainties associated with the estimates of urban area, UTC and C sequestration rate all contribute to the overall uncertainty of the estimates of CO₂ removals by urban trees. The result of these combined uncertainties using a Tier 2 Monte Carlo analysis approach provides an estimated total uncertainty of 28% for 1990 and 2012.

Table A3.5–12 Carbon Storage and Sequestration Densities in Urban Trees for Canadian RUs

Reconciliation Unit (RU)	Carbon Storage (t C ha ⁻¹)	Carbon Sequestration (t C ha ⁻¹ yr ⁻¹)
1 NL – Boreal Shield East	40	3.0
5 NS – Atlantic Maritime	62	3.4
6 PE – Atlantic Maritime	62	3.4
7 NB – Atlantic Maritime	62	3.4
11 QC – Atlantic Maritime	62	3.4
12 QC – Mixedwood Plains	58	2.4
15 QC – Boreal Shield East	40	3.0
16 ON – Boreal Shield West	40	3.0
17 ON – Mixedwood Plains	58	2.4
19 ON – Boreal Shield East	40	3.0
24 MB – Subhumid Prairies	55	2.9
28 SK – Boreal Plains	40	3.0
30 SK – Semiarid Prairies	55	2.9
34 AB – Boreal Plains	40	3.0
35 AB – Subhumid Prairies	55	2.9
37 AB – Semiarid Prairies	55	2.9
41 BC – Pacific Maritime	97	6.9
42 BC – Montane Cordillera	23	1.4

Note:
Source = Steenberg et al. (2021)

The uncertainties associated with 1990 and 2012 urban areas were not quantified by Statistics Canada. An error estimate of 10% was used for the 2012 urban area following the approach used in the United States' 2012 national GHG inventory report (U.S. EPA, 2013). The error associated with the 1990 urban area estimate was assumed to be slightly higher at 15% than for 2012, based on expert judgement. This approach is similar to the uncertainty estimate for boundary delineation (15%) used for developing forest conversion estimates (Leckie, 2011).

The uncertainty associated with UTC estimates was based on the standard error of the sampling approach calculated for each sampling period (1990 and 2012). Standard errors for the UTC estimates were low (0.2% for the national UTC estimate) given the very high number of sampling points used.

The uncertainty estimate for the national gross C sequestration rate (27%) was developed from a Monte Carlo analysis associated with each RU for the urban tree field data collected in Canada and for the city of Seattle. This uncertainty estimate does not include the estimation error related to the use of biomass equations or conversion factors or to measurement error (Nowak et al., 2013).

A3.5.7.2. Cropland Converted to Settlements

Data Sources

Urban and industrial expansion has been one of the main drivers of cropland conversion to settlements in Canada. Areas of cropland conversion to settlements were estimated based on the land-use maps for 1990, 2000 and 2010 developed in Huffman et al. (2015a). Areas of conversion for the 1990–2000 and 2000–2010 periods were calculated through spatial analysis for each RU and divided by the number of years in order to develop constant annual conversion rates. Areas of conversion were extrapolated after 2010. The total area of cropland converted to settlements for the 1990–2000 and 2000–2010 time periods was 184 kha and 115 kha, respectively, with the majority of change due to urban expansion in reporting zones 7 (Mixedwood Plains) and 11 (Subhumid Prairies). This is largely due to urban expansion in the main populated centres, such as Toronto, Hamilton, Oshawa, Montreal and Edmonton.

Uncertainty

Given that the highest conversion rates are caused by urban expansion, an independent assessment was conducted on the areas of conversion by comparing the land cover in each map against visual interpretation of ortho-rectified Landsat imagery over urban centres. The sampling strategy for this assessment was to perform the analysis on five main census metropolitan areas (CMA⁴¹), which contribute to 45% of the total area change from cropland to settlements. Polygons from the 2011 census were used to define the boundary of each CMA, and over 400 stratified random points were used to verify the land cover class in areas in which there were examples of either change or no-change from cropland to settlements, separated by a minimum distance of 1 km, to avoid statistical bias. The minimum mapping unit for the accuracy analysis was defined as a circle with radius of 100 m to prevent errors due to the presence of noise in each classified map. The class in each location was assigned based on the class of the majority of the pixels, to account for changes in land use. An overall accuracy of 80% and 84% was obtained for the areas of change computed from these maps, which concurs with the accuracy assessment carried out in Huffman et al. (2015a).

A3.5.7.3. Grassland Converted to Settlements

General Approach and Methods

Nearly half of Canada's land mass is in the Arctic and sub-Arctic regions and includes all land categories (IPCC, 2006), excluding Cropland. An approach was developed specifically for capturing the associated emissions by finding the land-use change and the amount of biomass stocks in this vast and remote landscape and included the following components: (i) manual digitizing of land-use polygons in Canada's Arctic/sub-Arctic for 1990, 2000 and 2010 based on ortho-rectified Landsat imagery and assessment of land-use change over about 359 million hectares, including areas in reporting zones 1 (Arctic Cordillera), 2 (Northern Arctic), 3 (Southern Arctic), 4 (Taiga Shield East), 5 (Boreal Shield East), 8 (Hudson Plains), 10 (Boreal Plains), 13 (Taiga Plains), 16 (Boreal Cordillera), 17 (Taiga Cordillera) and 18 (Taiga Shield West), north of 60°N latitude; and (ii) estimation of above-ground biomass based on field samples taken in Canada's Arctic/sub-Arctic regions between 2004 and 2010, covering the northern part of the Boreal Cordillera, Taiga Plains, Taiga Shield East, Taiga Shield West, Southern Arctic, Northern Arctic, and Arctic Cordillera.

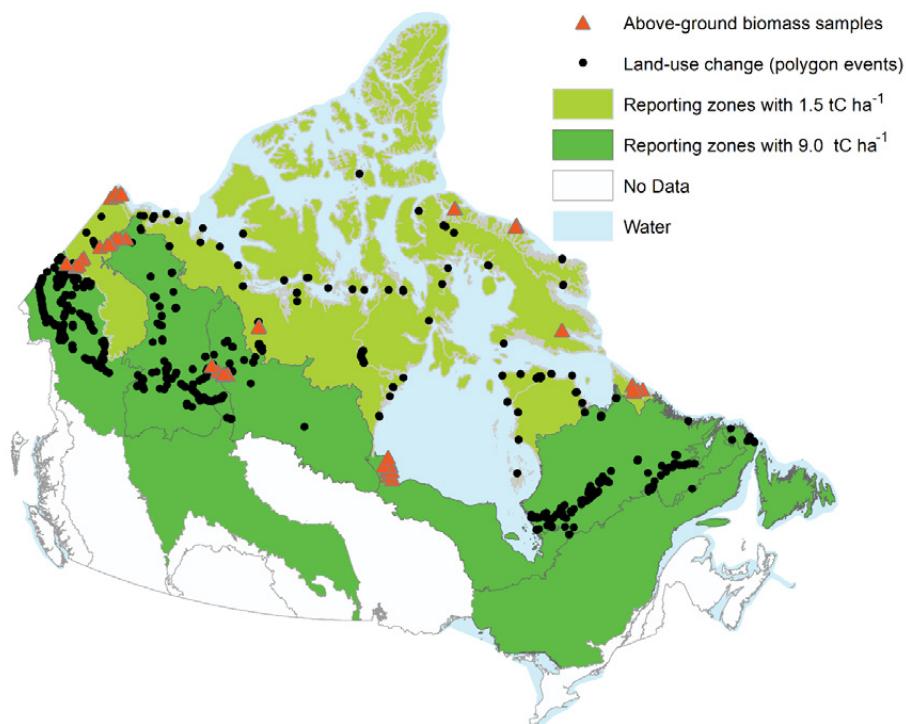
⁴¹ This term has been defined by Statistics Canada as the area consisting of one or more neighbouring municipalities with a population of 100 000 inhabitants or more.

A comprehensive, wall-to-wall analysis of land-use circa 1990, 2000 and 2010 was carried out based on image interpretation followed by manual digitization of the sites undergoing change (McGovern et al., 2016). A wide range of human disturbances such as airstrips, roads, power lines, seismic lines, urban areas, mines, reservoirs and even smaller features like well sites and some roadside clearings were identified using snow- and ice-free imagery. Analysis of existing GIS data sets denoting the occurrence of anthropogenic development were used to guide the search for areas with high probability of land-use change. Mapping was then expanded outwards from these regions based on the observation of additional disturbances. The resulting spatial data set provided the most comprehensive and complete mapping product for human disturbances in Canada's Northern region, and builds on previous boreal disturbance mapping activities conducted by ECCC. An interpretation guide similar to that of the Canadian Forest Service (Dyk et al., 2015) was used to guarantee consistency in the detection, digitization and categorization of disturbances. A total of 1135 scenes were used for the interpretation process (395 for 1990, 348 for 2000 and 392 for 2010).

Land-use change was derived from the difference in polygon areas for each date, providing an area of change between the time periods (i.e., 1990–2000, 2000–2010), which was divided by the total years in the time period to produce a constant annual rate of change. The same annual rate of land-use change was applied for the years prior to 1990 and following 2010. The pre-conversion land-use type for each of the land-use change polygons was based on available land cover maps (Wulder et al., 2008; Hermosilla et al., 2016), visual interpretation and vegetation indices of concurrent imagery to avoid including areas in other land-use categories (e.g., Forest Land, Cropland, Wetlands and Other Land). Furthermore, deforestation events above 60 degrees latitude were also used to confirm that areas determined to be forest conversion to settlements were excluded, to avoid double-counting.

The biomass lost was derived from statistical analysis of field samples surveyed between 2004 and 2011 over the Canadian north (Figure A3.5–21). Over 116 samples were collected in different land cover types (e.g., shrubs, grass tundra, wetland, forest and barren land) in eight reporting zones. The vegetation in this region consists of forest patches in the Boreal Cordillera and Taiga Plains, but predominantly low vegetation composed of sparse shrubs, mixed grass-dwarf shrub, lichen, moss tussock sedge, bare soil and Arctic willow tundra for the remaining reporting zones. Due to diversity of vegetation types and landscapes over the extent of this region, field samples on forest were excluded and the remaining samples were grouped into two classes: high and low vegetation. This grouping was based on the fact that, after statistical examination

Figure A3.5–21 Location of Land-Use Events and Field Samples of Above-Ground Biomass in Canada's North



Note: More southerly reporting zones are attributed to the 9 tC ha^{-1} biomass class, as some sites border on the northernmost boundary of these reporting zones.

of the above-ground biomass values, there was significant variability in the sampled vegetation types between reporting zones. As an initial implementation, the mean of the samples for reporting zones 1 (Arctic Cordillera), 2 (Northern Arctic), 3 (Southern Arctic) and 17 (Taiga Cordillera) was used to obtain a single value of above-ground biomass (1.5t C ha^{-1}) that was applied to all of them—areas with “low” vegetation types. Similarly, a single average value (9 tC ha^{-1}) from all samples in the remaining reporting zones (Taiga Plains, Taiga Shield West, Boreal Cordillera and Hudson Plains) was used and applied for the remaining areas—areas with “high” vegetation. Reporting zones with land-use change data but without field samples (i.e., Taiga Shield East, Boreal Shield East and Boreal Plains) were assigned to either of the two groups of low or high vegetation based on an analysis of vegetation indices. Emissions from land-use change were estimated by multiplying the annual area of land-use change by their respective biomass lost factor to obtain C stock changes. Annual area rates and emissions for years after 2010 were extrapolated from the 2000–2010 period, assuming a constant yearly rate.

The biomass factor obtained for each of the two vegetation groups was assessed based on the vegetation characteristics of each ecozone (Marshall et al., 1999) and values in the literature (Shaver and Chapin, 1991; Hudson and Henry, 2009; Gould et al., 2003) and was also compared against default values provided by the 2006 IPCC guidelines for the boreal and cool temperate regions (IPCC, 2006). All land-use change activities involved conversion of Arctic tundra vegetation to settlements, and all pre-conversion biomass C was deemed emitted upon clearing.

Uncertainty

The error propagation approach was used to estimate uncertainty using a 95% confidence interval. The percentage of uncertainty for the above-ground biomass volume was 70% for ecozones with low vegetation and 80% for all the other ecozones, based on the coefficient of variation. The uncertainty of the total land-use change area was estimated to be 30%, based on random sampling and image interpretation. A 20% uncertainty was used for the C content, estimated to be 50% of the dry biomass weight, based on the IPCC guidelines (IPCC, 2006). Using these values, an overall uncertainty of 87% was estimated for this category.

A3.6. Methodology for Waste Sector

The Waste sector consists of four categories: Solid Waste Disposal (Landfills), Biological Treatment of Solid Waste, Incineration and Open Burning of Waste, and Wastewater Treatment and Discharge. This section of Annex 3 details the accounting methodologies that are used to describe the greenhouse gas (GHG) emission estimates for these categories with a focus on the following categories and gases:

- Methane (CH_4) emissions from solid waste disposal (municipal solid waste and Industrial Wood Waste Landfills)
- CH_4 and Nitrous oxide (N_2O) emissions from Biological Treatment of Solid Waste (composting and anaerobic digestion)
- Carbon dioxide (CO_2), CH_4 and N_2O emissions from waste incineration (municipal solid waste, hazardous, clinical and sewage sludge waste)
- CH_4 and N_2O emissions from Wastewater Treatment and Discharge (municipal and industrial)

A3.6.1. Emissions from Solid Waste Disposal (Landfills)

A3.6.1.1. General Approach and Methods

In Canada, the Solid Waste Disposal (Landfills) category comprises two types of landfills: municipal solid waste (MSW) landfills and industrial wood waste (WW) landfills. The treatment and disposal of solid waste produces significant amounts of CH_4 , in addition to smaller amounts of CO_2 . However, as the CO_2 is primarily from biogenic sources, it is not included in total waste emissions. Emissions of N_2O from landfills are not estimated as they are not significant, and no quantification methodology is provided by the IPCC (IPCC, 2006, 2019).

Emissions for MSW and WW landfills are calculated separately at the provincial and territorial level. Emissions from MSW landfills are reported to the UNFCCC under category 5.A.1, Managed Waste Disposal Sites, while emissions from WW landfills are reported under category 5.A.2, Unmanaged Waste Disposal Sites.

Methane generated from landfills is calculated using a first-order decay (FOD) model, in accordance with Volume 5, Chapter 3, of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, hereafter referred to as the 2006 IPCC Guidelines (IPCC, 2006). The FOD model considers that waste deposited in any given year decays over several decades at an initially high-rate, which decreases over time (Figure A3.6–1).

Landfill gas capture, flaring and utilization practices are increasingly common in Canadian landfills. The amount of CH_4 in landfill gas captured by facilities is subtracted from the total amount generated within the landfill to determine the amount that is actually released annually from the decomposing waste. A small amount of CH_4 is released from flaring and utilization of landfill gas (combustion for heat or energy). The amount of CH_4 ultimately emitted by a landfill is further reduced by the oxidation of some of the CH_4 into CO_2 by methanotrophic bacteria in landfill cover material.

The calculation of CH_4 emissions from waste landfilled can be summarized with Equation A3.6–1. The stepwise calculations that make up the FOD model are represented by Equation A3.6–2 to Equation A3.6–5. Methane generation is calculated by material.

Equation A3.6–1 (modified from the 2006 IPCC Guidelines Eq. 3.1)

$$\text{CH}_4 \text{ emitted}_T = [\text{CH}_4 \text{ generated}_T - R_T] \times (1 - OX) + (\text{CH}_4 \text{ flared}_T \times (1 - \text{Efcy}_{flr}))$$

$\text{CH}_4 \text{ emitted}_T$	=	CH_4 emitted from landfills in year T (tonne)
T	=	inventory year
$\text{CH}_4 \text{ generated}_T$	=	CH_4 generated by landfilled waste in year T (tonne)
R_T	=	CH_4 recovered through landfill gas capture in year T (tonne)
OX	=	oxidation factor (fraction)
$\text{CH}_4 \text{ Flared}_T$	=	amount of CH_4 flared in year T (tonne)
Efcy_{flr}	=	flaring efficiency (fraction)

Note: CH_4 emitted from utilization of landfill gas for energy is calculated and reported as part of the Energy section.

Equation A3.6–2 (modified from 2006 IPCC Guidelines Eq. 3.2)

$$DDOC_{m,T} = \text{Waste deposited}_{m,T} \times DOC_m \times DOC_{fm}$$

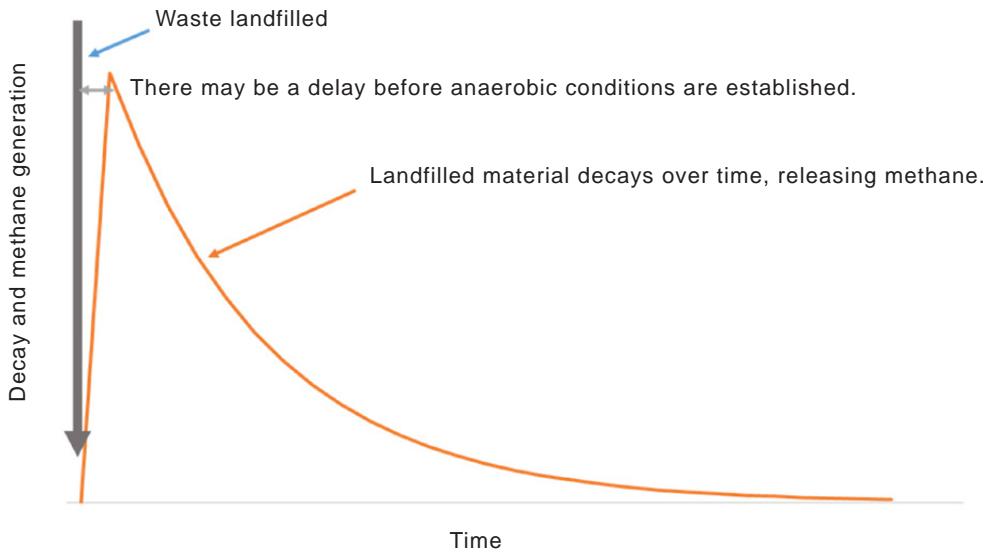
$DDOC_{m,T}$	= mass of decomposable degradable organic carbon from material m that is deposited in year T (tonne)
m	= type of waste material type deposited (e.g., food, paper).
T	= year
$\text{Waste deposited}_{m,T}$	= mass of waste material m deposited in year T (tonne)
DOC_m	= fraction of degradable organic carbon in waste type m
DOC_{fm}	= fraction of DOC that can/does decompose, for waste type m

Equation A3.6–3 (modified from the 2006 IPCC Guidelines Eq. 3.4)

$$DDOCma_T = DDOCmd_y + (DDOCma_{y-1} \times e^{-k})$$

T	= inventory year
$DDOC_{maT}$	= DDOC _m (decomposable degradable organic carbon, from waste material m) accumulated in the landfill at the end of year (tonne)
$DDOC_{maT-1}$	= DDOC _m accumulated in the landfill at the end of year (T-1) (tonne)
$DDOC_{mdT}$	= DDOC _m deposited into the landfill in year T (tonne)
k	= decay rate constant (year ⁻¹)

Figure A3.6–1 Representation of First Order Decay Emissions from One-Time Waste Deposition in Landfill



Equation A3.6–4 (modified from the 2006 IPCC Guidelines Eq. 3.5)

$$DDOC_m \text{ decomp}_T = DDOC_{m,T-1} \times (1 - e^{-k})$$

$DDOC_m \text{ decomp}_T$	=	DDOC _m (decomposable degradable organic carbon, from waste material m) that decomposed in the landfill in year T (tonne)
T	=	inventory year
$DDOC_{m,T-1}$	=	DDOC _m accumulated in the landfill at the end of year (T-1) (tonne)
k	=	decay rate constant (year^{-1})

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Equation A3.6–5 (2006 IPCC Guidelines Eq. 3.6)

$$\text{CH}_4 \text{ generated} = DDOC_m \text{ decomp}_{m,T} \times \text{FracCH}_4 \times 16/12 \times MCF$$

$\text{CH}_4 \text{ generated}$	=	amount of CH ₄ generated from decomposable material
$DDOC_m \text{ decomp}_{m,T}$	=	DDOC _m (decomposable degradable organic carbon, from waste material m) that decomposed in year T (tonne)
FracCH_4	=	fraction of CH ₄ by volume, in landfill gas
$16/12$	=	molecular weight ratio CH ₄ /C
MCF	=	methane correction factor

The parameters used, including material-specific DOC and DOC_f values and decay rate constants, are presented in section A3.6.1.2 for municipal solid waste landfills and in section A3.6.1.3 for industrial wood waste landfills. For more details on the parameters themselves, such as how they are developed and guidance on selecting appropriate values, see Volume 5, Chapter 3, of the 2006 IPCC Guidelines (IPCC, 2006).

A3.6.1.2. Municipal Solid Waste (MSW) Landfills

A3.6.1.2.1. Model Parameters for MSW Landfills

Degradable Organic Carbon

The degradable organic carbon (DOC) represents the portion of the organic carbon in the waste that is available for decomposition. It is a characteristic of the materials deposited. DOC is generally measured as a fraction of wet weight of the waste material, with the exception of sewage sludge, which is measured in dry weight. The total DOC is determined by the composition of the waste entering into the landfill. The material-specific DOC values used are shown in Table A3.6–1.

Fraction of Degradable Organic Carbon Which Decomposes

The decomposable degradable organic carbon (DOC_f) is an estimate of the amount of DOC in waste that actually decomposes in the landfill. The material-specific DOC_f values are taken primarily from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019). The values are shown in Table A3.6–1.

Waste classifications varied over time with each characterization study. In other words, a given waste type might only be used in one characterization, but not used in others characterizations. Some examples are “Rubber and Leather” which were grouped together in the characterization study by SMI (SMI, 2016), or the category “Other Inert,” which is the remainder of non-organic waste from the SMI study, which only characterized waste that had organic components.

Methane Correction Factor

The CH₄ correction factor (MCF) accounts for the decomposition of waste under different management practices. It is used to account for the fact that unmanaged landfills produce less CH₄ from a given amount of waste than anaerobic managed landfills (IPCC, 2006). All municipal solid waste landfills in Canada are assumed to be anaerobic managed landfills (MCF = 1.0).

Decay Rate Constant (k)

The decay rate constant, k, represents the rate at which CH₄ is generated in the FOD reaction after waste has been landfilled. The value of k can be affected by moisture content, nutrient availability, temperature and pH, among other factors. The 2006 IPCC Guidelines decay rate constants, k, for the boreal-temperate wet and dry climate zones are used (IPCC,

2006). The “wet” and “dry” climates are defined by the ratio of mean annual precipitation to potential evapotranspiration: wet climates have a mean annual precipitation that is greater than the potential evapotranspiration, while dry climates have a mean annual precipitation that is less than the potential evapotranspiration. The material-specific decay rate constants, by climate, are shown in Table A3.6–2. The estimates of waste landfilled by climate zone, for each province, is discussed in section A3.6.1.2.2.

Applying decay rate constants by material, rather than as bulk averages for all waste, better captures both the differences between materials and the variations in waste composition over time. For example, food waste has a decay rate constant of 0.185 or a half-life 3.7 years in wet climates, whereas paper has a decay rate constant of 0.06 or a half-life 11.6 years in the same climate. Each material will produce emissions at different rates after initial deposition in landfills. Again, taking the example of food and paper, food will exhibit rapid decay and release of emissions early on, dropping off more quickly. In contrast, paper will initially produce less emissions, but those emissions will not decrease as quickly, resulting in relatively higher rates at later periods.

Fraction of Landfill Gas that is CH₄

The FracCH₄ value in Equation A3.6–5 represents the CH₄ fraction of landfill gas generated by anaerobic decomposition within the landfill, by volume. The 2006 IPCC Guidelines (IPCC, 2006) recommended default of 0.5 is used for all time periods and regions.

Methane Recovery

Methane emissions are reduced by the recovery of landfill gas, which is commonly practiced in Canada. A study commissioned by Environment and Climate Change Canada (ECCC) found that approximately 90% of medium- and large-sized landfills surveyed currently employ landfill gas capture technologies (GHD, 2017). Methane in landfill gas is destroyed (oxidized to CO₂) by flaring or when combusted for energy purposes. Methane escaping flaring due to combustion inefficiencies are included in the emission totals. Methane escaping combustion for energy purposes due to inefficiencies are estimated and reported as part of the Energy sector and are not included in the Waste totals.

Table A3.6–1 Waste Material Degradable Organic Carbon Content and Fraction of Degradable Organic Carbon That Does Decay

Material	DOC	DOC Source	DOC _f	DOC _f Source
Food	0.15	IPCC (2006)	0.7	IPCC (2019)
Paper	0.4		0.5	
Textiles	0.24		0.5	
Wood	0.43		0.1	
Yard and Garden	0.2		0.7	
Leather	0.39		0.1	
Rubber	0.39		0	IPCC (2006), Footnote Table 2.4 (Natural rubber doesn't decompose in landfill)
Rubber and Leather	0.39		0.1	
Soil and Dirt	0.03	ECCC Estimate	0.1	IPCC (2019), “less decomposable waste”
Soiled Paper	0.4	IPCC (2006) (paper)	0.5	
Diapers	0.24	IPCC (2006)	0.5	
Pet Waste	0.24	ECCC Estimate	0.5	
Construction Debris	0.22	ECCC Estimate	0.5	
Other – Unknown	0.5	IPCC (2006), Bulk	0.5	
Plastics	0	IPCC (2006)	0.5	
Sludge (Wet Wt)	0.3	IPCC (2019), Default	0.5	
Sludge (Dry Wt)	0.74155	ECCC Analysis	0.5	ECCC estimate
Oils Paints and Solvents	0	ECCC Estimate	0	
Glass	0	IPCC (2006)	0	
Metals	0	IPCC (2006)	0	
Hazardous	0	ECCC Estimate	0	
Concrete	0	IPCC (2006)	0	
Asphalt	0	ECCC estimate	0	
Other Inert	0		0	
Electronics	0		0	
Ash	0		0	

Table A3.6-2 Decay Rate Constants and Half-Lives of Waste Materials, by Climate

Material	Decay Rate, k (yr ⁻¹)		Half-Life (yr)		Source
	Dry	Wet	Dry	Wet	
Food	0.06	0.185	11.6	3.7	IPCC (2006)
Paper	0.04	0.06	17.3	11.6	IPCC (2006)
Textiles	0.04	0.06	17.3	11.6	IPCC (2006)
Wood	0.02	0.03	34.7	23.1	IPCC (2006)
Yard and Garden	0.05	0.1	13.9	6.9	IPCC (2006)
Soiled Paper	0.05	0.1	13.9	6.9	IPCC (2006), Moderately Degrading Waste
Leather	0.01	0.01	69.3	69.3	ECCC estimate
Rubber	0.01	0.01	69.3	69.3	ECCC estimate
Diapers	0.06	0.185	11.6	3.7	IPCC (2006), Sewage Sludge
Pet Waste	0.06	0.185	11.6	3.7	
Sewage Sludge (dry wt)	0.06	0.185	11.6	3.7	
Construction Debris	0.02	0.03	34.7	23.1	IPCC (2006), Wood
Soil and Dirt	0.05	0.09	13.9	7.7	IPCC (2006), Default Bulk Waste
Plastics	0.05	0.09	13.9	7.7	
Other – Unknown	0.05	0.09	13.9	7.7	
Oils Paints and Solvents	0.05	0.09	13.9	7.7	
Glass	0.05	0.09	13.9	7.7	
Metals	0.05	0.09	13.9	7.7	
Hazardous	0.05	0.09	13.9	7.7	
Concrete	0.05	0.09	13.9	7.7	
Asphalt	0.05	0.09	13.9	7.7	
Electronics	0.05	0.09	13.9	7.7	

Emissions from Flaring and Utilization

Combustion by flaring is considered to be 99.7% efficient. CH₄ released from flaring is added to the CH₄ released from landfills to obtain the total CH₄ emitted. CH₄ released from combustion (utilization) of landfill gas is reported in the Energy sector.

Oxidation through Landfill Cover

Methane emissions from landfills are reduced further by the oxidation of CH₄ into CO₂ by methanotrophic bacteria in landfill cover material. A broad range of provincial regulations mandate that Canadian landfills be capped with a daily cover of material such as soil, compost, woody material or fill. When a landfill is no longer operational, it is capped with a final, more robust cover.

The 2006 IPCC Guidelines' (IPCC, 2006) default factor of 0.1 for managed landfills covered with CH₄ oxidizing material is used for all regions and time periods.

A3.6.1.2.2. Data Sources Municipal Solid Waste (MSW) Landfills

Waste deposited in municipal landfills in Canada is an aggregate of waste from industrial, commercial and institutional (ICI), construction and demolition (C&D) and residential sources, but also includes sewage sludge, which is a by-product of wastewater treatment (section A3.6.4).

There is no consistent and comprehensive data set of waste landfilled in Canada. There are, however, data available on the total amount of municipal solid waste (MSW) disposed, which is the solid waste from residential, ICI and C&D sources that is landfilled, incinerated and exported. Note that waste disposed does not include sewage sludge (which must be quantified separately), or waste diverted at source for recycling or compost.

The total waste landfilled can be determined from the amount disposed after accounting for amounts incinerated and amounts exported, and adding the amount of sewage sludge landfilled.

Equation A3.6–6 Waste Landfilled in Municipal Landfills

$$\text{Total Waste Landfilled} = [\text{MSW}_{\text{Disposed}} - \text{MSW}_{\text{Incinerated}} - \text{MSW}_{\text{Exported}}] + \text{Sewage Sludge}_{\text{Landfilled}}$$

Total Waste Landfilled	=	mass of waste landfilled, tonnes
$\text{MSW}_{\text{Disposed}}$	=	mass of municipal solid waste (MSW) disposed in Canada, which includes solid waste landfilled, incinerated and exported, tonnes
$\text{MSW}_{\text{Incinerated}}$	=	mass of MSW incinerated in Canada, tonnes
$\text{MSW}_{\text{Exported}}$	=	net mass of MSW exported (imported) to (from) the United States, tonnes
$\text{Sewage Sludge}_{\text{Landfilled}}$	=	mass of sewage sludge landfilled, tonne

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Quantity of Waste Disposed

Municipal solid waste (MSW) disposed includes waste from institutional, commercial and industrial (ICI), construction and demolition (C&D) and residential sources. MSW disposal data are required from 1941 onward. Two primary data sources and calculation approaches are used: per capita disposal rates from 1941 to 1993, and reported disposal quantities from 1994 onward.

Waste disposal data from 1994 onward are obtained through Statistics Canada's biennial Waste Management Industry Survey (Statistics Canada, n.d.[a]) which compiles waste disposal data for every even year. Disposal quantities are linearly interpolated for intermediary years (e.g., 1995, 1997, etc.). When survey data have not yet been released for the latest inventory year, the most recent survey results are held constant.

Waste disposal quantities for PEI and the territories are suppressed for the years 1994 to 2016 in Statistics Canada tables, for confidentiality reasons, but available from 2018. Waste disposal data for PEI has been obtained from the province for the years 1995 to 2000 and 2004 to 2018. Data gaps were bridged through linear interpolation. Waste disposal for the territories from 1994 onward is estimated using the 2018 per capita waste disposal rate of 0.73 tonnes/capita/year for the three territories.

Waste disposal amounts for 1941 to 1980 for all provinces and territories are calculated using national per capita disposal rates obtained from Levelton (Levelton, 1991) and population from Statistics Canada (Statistics Canada, n.d.[b], n.d.[c]). Levelton presented per capita disposal rates at 5- to 20-year increments. Disposal rates were linearly interpolated for intermediary years. Disposal rates for 1985 and 1990 were published in the report, but these were an extrapolation at the time and are not used. Disposal rates for the provinces and territories from 1981 to 1993 are linearly interpolated between the per capita disposal rate in 1980 from Levelton (1991) and the per capita disposal rate in 1994 (1995 in PEI) from Statistics Canada.

Waste Incinerated

Data on the amount of waste incinerated are discussed in section A3.6.3.

Waste Exported

Waste exports are not directly tracked by Canada. An ECCC internal database of waste exports to the United States since 1989 has been compiled from U.S. state databases and congressional reports and by contacting state officials. Where data are not available for the most recent reporting years, the last data point is held constant.

Waste Landfilled

The total amount of waste landfilled is calculated from the municipal solid waste disposed, accounting for exports and incineration and quantities of sludge landfilled. The final amount of waste landfilled, as determined from waste disposed, incinerated and exported, is shown in Table A3.6–3.

Sewage Sludge Landfilled

Sewage sludge produced is estimated as part of the wastewater treatment organics flow calculations. The amount of sewage sludge landfilled can be estimated in a manner similar to that used for MSW, accounting for incineration and export, but also anaerobic digestion, compost and land application. Accounting to determine sewage sludge landfilled is shown in section A3.6.4 and Equation A3.6–28.

Table A3.6-3 Waste Landfilled in Municipal Solid Waste Landfills 1990–2020 (millions of tonnes)

Year	Food	Paper	Diapers and Pet Waste	Textiles	Rubber and Leather	Sludge (Dry Wt)	Yard and Garden	Wood	Construction Debris	Other	Inert	Total
1990	2.60	5.78	0.00	0.20	0.23	0.17	2.57	0.82	0.89	1.69	3.57	18.52
1991	2.65	5.86	0.00	0.21	0.24	0.17	2.61	0.83	0.91	1.72	3.62	18.82
1992	2.55	5.51	0.00	0.21	0.24	0.17	2.50	0.78	0.86	1.66	3.42	17.90
1993	2.72	5.93	0.00	0.22	0.25	0.17	2.68	0.84	0.93	1.77	3.68	19.19
1994	2.90	6.40	0.00	0.23	0.26	0.16	2.87	0.90	0.99	1.88	3.96	20.55
1995	2.84	6.30	0.00	0.22	0.25	0.16	2.80	0.89	0.97	1.83	3.89	20.15
1996	2.69	5.94	0.00	0.21	0.24	0.15	2.64	0.83	0.91	1.72	3.67	19.00
1997	2.70	5.98	0.00	0.21	0.24	0.15	2.65	0.84	0.92	1.72	3.70	19.11
1998	2.70	5.99	0.00	0.21	0.24	0.15	2.65	0.84	0.91	1.73	3.71	19.13
1999	2.86	6.41	0.00	0.22	0.25	0.15	2.81	0.91	0.97	1.83	3.95	20.36
2000	2.95	6.63	0.00	0.22	0.25	0.14	2.90	0.94	1.00	1.88	4.09	21.00
2001	2.92	6.54	0.00	0.22	0.25	0.14	2.87	0.93	0.99	1.87	4.04	20.77
2002	3.90	5.52	0.42	0.55	0.17	0.12	1.15	2.34	0.00	0.69	6.28	21.14
2003	3.90	5.42	0.42	0.55	0.17	0.12	1.18	2.32	0.00	0.67	6.18	20.93
2004	3.80	5.07	0.43	0.56	0.16	0.11	1.20	2.52	0.00	0.63	6.37	20.85
2005	3.86	5.12	0.44	0.57	0.17	0.11	1.27	2.58	0.00	0.63	6.45	21.20
2006	4.05	5.31	0.48	0.59	0.17	0.10	1.40	2.58	0.00	0.65	6.55	21.88
2007	4.05	5.36	0.48	0.60	0.17	0.10	1.41	2.59	0.00	0.67	6.59	22.02
2008	4.03	5.41	0.47	0.59	0.17	0.10	1.46	2.54	0.00	0.69	6.43	21.89
2009	4.02	5.44	0.47	0.59	0.17	0.09	1.44	2.53	0.00	0.70	6.46	21.91
2010	4.03	5.32	0.49	0.60	0.17	0.09	1.44	2.39	0.00	0.68	6.30	21.51
2011	4.06	5.43	0.49	0.60	0.18	0.08	1.44	2.43	0.00	0.69	6.41	21.81
2012	4.08	5.45	0.50	0.61	0.18	0.08	1.42	2.35	0.00	0.69	6.37	21.73
2013	3.91	5.06	0.48	0.59	0.17	0.07	1.41	2.24	0.00	0.64	5.98	20.55
2014	3.86	5.00	0.49	0.60	0.17	0.06	1.41	2.31	0.00	0.63	6.05	20.58
2015	4.84	2.34	1.17	0.29	0.26	0.06	0.93	2.09	1.91	2.99	4.01	20.89
2016	4.74	2.28	1.16	0.28	0.26	0.06	0.94	1.98	1.82	2.90	3.90	20.32
2017	4.66	2.24	1.14	0.28	0.26	0.06	0.93	1.94	1.80	2.86	3.83	20.00
2018	4.83	2.32	1.20	0.29	0.27	0.07	0.96	2.01	1.86	2.97	3.99	20.77
2019	4.98	2.40	1.24	0.30	0.27	0.06	0.98	2.08	1.90	3.06	4.12	21.39
2020	5.19	2.50	1.29	0.31	0.29	0.06	1.02	2.19	1.97	3.20	4.33	22.35

Notes:

Inert includes Glass, Metals, Ash, Concrete, Asphalt, Plastics, Other Inert, Electronics

Full data set, by Province, Territory and climate region available on request

Municipal Solid Waste Characterization

Waste characterization is the quantification of the material composition of the waste. Municipal solid waste is characterized after accounting for exports and incineration. Sewage sludge is added to the totals landfilled afterwards and is not included in or impacted by the characterization.

Waste characterization studies with sufficient scope to describe waste composition across all regions of Canada are challenging and costly. As a result, they tend to be infrequent. Ideally, waste is characterized separately for every region (province and territory) and for all waste streams or sources. Waste sources, which are available from the Statistics Canada Waste Management Industry Survey and which are used for some characterizations, consist of industrial, institutional and commercial (ICI), construction and demolition (C&D) and residential waste streams.

The level of detail and material classifications vary between characterization studies. Some studies provide regional characterizations, or even characterization by region and waste source. Each characterization study uses slightly different classifications for waste material. For example, some group rubber and leather, others do not; only the most recent characterization study (ECCC, 2020a) includes pet waste.

The characterization study by NRCAN (2006) included details for both waste disposed and recycling. Municipal recycling in Canada only started in earnest in the 1990s. To reflect the waste composition before recycling, the recycling characterization and waste characterization from NRCAN (2006) were combined for the 1976 to 1989 period. The characterization by Bond and Straub (1973) is for the United States and was used on the assumption that the Canadian waste profile at the time was reasonably similar. The SMi characterization did not quantify material classes deemed to have low or negligible organic content (SMi, 2016).

A full characterization of waste landfilled by waste source, including sewage sludge, is shown in Chapter 7, Figure 7.1. Sources used and applicable timeframes for each source are summarized by general waste type in Table A3.6–4.

Waste Deposited by Climate Region

The 2006 IPCC Guidelines (IPCC, 2006) define a wet climate as having a mean annual precipitation greater than the mean annual potential evapotranspiration and a dry climate as having a mean annual precipitation less than the mean annual potential evapotranspiration. To determine the proportion of waste landfilled in either wet or dry climate zones (by province), the known quantities of waste disposed of at the largest (approximately 300) landfills were mapped against long-term mean annual precipitation and mean annual potential evapotranspiration (1941 to 2018; Climate Research Unit, University of East Anglia, 0.5 degree spatial resolution; CRU Version 4.03; Figure A3.6–2). The resulting proportions of wet and dry climate for each province and territory are found in Table A3.6–5.

Table A3.6–4 Waste Characterization Sources Used

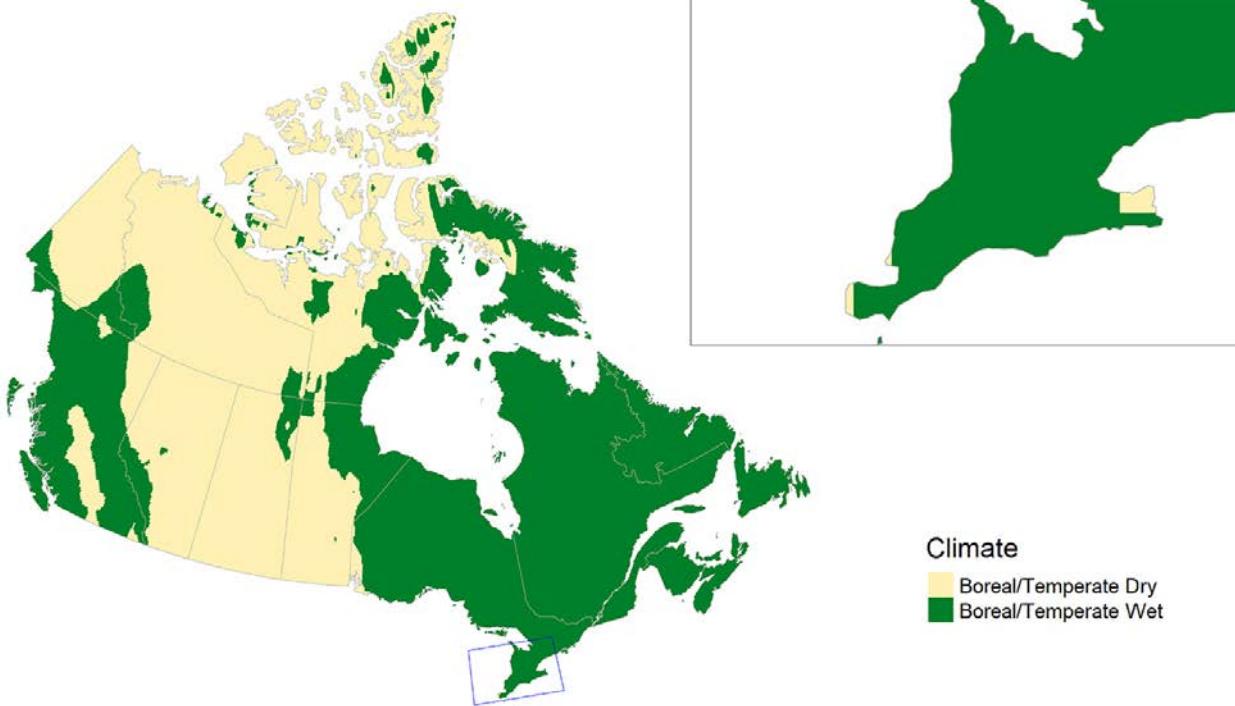
Characterization	From	To	Characterized By	Notes
Bond and Straub (1973)	1941	1975		Composition is not specific to Canada
NRCAN (2006) (with recycling re-categorized as disposed)	1976	1989	Region	Recycling added to waste disposed (as recycling only truly began in earnest in Canada in the 1990s)
NRCAN (2006)	1990	2001	Region	
SMi (2016)	2002	2014	Region and Waste Source (Residential, C&D, ICI)	This study only characterized waste with organic content. All other waste was lumped together as "other inert"
ECCC (2020a)	2015		Region and Waste Source (Residential, C&D, ICI)	

Table A3.6–5 Proportion of Waste Landfilled in Wet or Dry Climate Regions of each Province or Territory

Region	Dry	Wet
AB	1	0
BC	0.29	0.71
MB	1	0
NB	0	1
NL	0	1
NS	0	1
NT	1	0
NU	0.5	0.5
ON	0.07	0.93
PE	0	1
QC	0	1
SK	1	0
YT	1	0

Figure A3.6–2 Long-Term Climate Regions in Canada

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Methane Recovery

Landfill gas capture at large municipal solid waste facilities is common across Canada. Given its relatively high concentration of CH₄, captured landfill gas can be used for heat and/or electricity production. Facilities may also choose to simply flare the captured gas. Note that any emissions resulting from the production of heat or electricity using landfill gas are reported under the Energy sector. See Chapter 7, Figure 7–1, and Table A3.6–6 for CH₄ recovery totals.

Data on landfill gas capture are collected through biennial, voluntary surveys conducted by Environment and Climate Change Canada (ECCC, 2020b). Gaps in the time series for reporting facilities are filled using linear interpolation. If data gaps exist before the earliest record for a facility, the landfill gas recovery is extrapolated back in time to the year when operation of flaring or CH₄ utilization first began at that facility (and not extrapolated if these dates are unknown). If survey results for the latest years are not yet available, the most recent data are held constant.

The amount of CH₄ recovered for each province is calculated from the volume of gas captured by all facilities in that province. National totals are shown in Table A3.6–6.

While flaring of captured landfill gas greatly reduces CH₄ emissions when utilization is not viable, it is not a 100% efficient process. A flaring efficiency of 99.7% is used to calculate the total CH₄ generated from landfills (U.S. EPA, 1995). Methane emissions from utilization are reported in the Energy section.

Table A3.6–6 CH₄ Generated, Recovered and Emitted from Municipal Solid Waste Landfills in Canada

Year	CH ₄ Generated in Landfills (kt)	CH ₄ Flared (kt)	CH ₄ Emitted from Flaring (kt)	CH ₄ Utilized ^a (kt)	CH ₄ Oxidized by Landfill Cover (kt)	Total CH ₄ Recovery (Flaring + Utilization) (kt)	Total CH ₄ Emitted (kt)
1990	983	56	0.2	56	87	112	784
1991	1023	72	0.2	84	87	155	781
1992	1061	77	0.2	102	88	178	795
1993	1091	83	0.2	109	90	191	810
1994	1126	87	0.3	121	92	208	826
1995	1166	112	0.3	127	93	239	835
1996	1200	178	0.5	116	91	293	816
1997	1224	236	0.7	94	89	330	805
1998	1248	236	0.7	83	93	319	836
1999	1269	225	0.7	76	97	300	872
2000	1297	221	0.7	78	100	299	898
2001	1326	219	0.7	113	99	332	895
2002	1352	214	0.6	119	102	331	919
2003	1356	203	0.6	131	102	333	921
2004	1357	207	0.6	151	100	357	900
2005	1354	177	0.5	157	102	333	919
2006	1351	186	0.6	142	102	328	920
2007	1352	185	0.6	161	101	345	907
2008	1354	200	0.6	166	99	366	889
2009	1355	203	0.6	197	95	399	860
2010	1355	212	0.6	231	91	442	822
2011	1355	206	0.6	236	91	441	823
2012	1356	205	0.6	235	92	440	825
2013	1357	216	0.6	229	91	445	822
2014	1352	222	0.7	225	91	446	816
2015	1346	231	0.7	201	92	431	824
2016	1362	238	0.7	197	93	434	834
2017	1372	223	0.7	199	95	421	856
2018	1378	210	0.6	206	96	415	867
2019	1389	207	0.6	209	97	415	876
2020	1401	199	0.6	219	98	418	885

Note:

a. CH₄ emitted from combustion for utilization as heat and power is captured in Energy

A3.6.1.2.3. Emissions Estimates for MSW Landfills

Methane emissions are the net result of CH₄ generated (estimated using the first-order decay model) minus CH₄ recovery and oxidation and emissions from flaring and utilization. Emissions from CH₄ utilization for energy are reported in the Energy section, and not included in Waste sector totals. Estimates are presented in Table A3.6–6.

A3.6.1.3. Industrial Wood Waste Landfills

A3.6.1.3.1. Data Sources

Wood waste estimates are based on the amount of wood waste residuals estimated to be disposed of in private landfills. This category captures wood waste that does not enter waste management streams in Canada and thus is not accounted for in the MSW component of the Solid Waste Disposal (Landfills) category.

Wood waste disposed of in Canada is assumed to come from two sources; the solid wood industry and the pulp and paper industry. Quantities of wood waste residuals from 2005 onwards are derived from a literature review, from consultations with industry experts and from survey data prepared by the National Council for Air and Stream Improvement (ECCC, 2020c; NCASI, 2020). Given that the repurposing of wood waste is increasingly preferred over landfilling, it is assumed that the amount of wood waste disposed of is decreasing rapidly. Specific to Canadian sawmills, the combination of increasingly lower surplus residues, combined with their use as a resource (energy or otherwise) and the necessity in maintaining profit

margins, there is little incentive for facilities to landfill any waste residues. As a result, it is believed that sawmills have landfilled little to no waste residuals since 2010. However, landfilling of residuals in the pulp and paper sector in Canada is ongoing; the quantity of residuals landfilled for this sector is based on NCASI survey data. As this data was only available at the national level, provincial level ratios were developed using waste emissions reported by facilities to the Greenhouse Gas Facility Reporting Program that were then applied to the national values.

Quantities of wood waste disposed of between 1990 and 2004 for the pulp and paper sector and between 1990 and 2010 for the solid wood industry are based on three studies published by Natural Resources Canada (NRCan, 1997, 1999, 2005). For this time period, it is estimated that 80% of wood waste is disposed of by the solid wood industry, while the remaining 20% is disposed of by the pulp and paper industry (MWA Consultants Papricon, 1998). Of the total volume of waste disposed, the amount sent to private landfills is assumed to be 15% for the solid wood industry and 86% for the pulp and paper industry (NRCan, 1997). The estimated amount of wood waste disposed of is then converted from “bone dry” units to “hydrated” units using a wood waste moisture content of 20% (Tchobanoglou et al., 1993). Given the lack of historical data, quantities used for the time period 1970–1990 are assumed to be the same as 1990 levels. The national values for wood waste disposed of and landfilled are shown in Table A3.6–7. The final estimated amount of wood waste landfilled by province is shown in Table A3.6–8.

Table A3.6–7 Quantity of Industrial Wood Waste Landfilled in Canada (1990–2020)

Year ^a	Landfilled		
	Pulp and Paper (BDt)	Solid Wood (BDt)	Total ^b (Hydrated Tonnes)
1970–1990	1 557 513	1 086 637	3 305 187
1991	1 478 924	1 030 904	3 137 285
1992	1 400 335	976 718	2 971 315
1993	1 321 746	922 531	2 805 345
1994	1 243 157	868 344	2 639 375
1995	1 164 567	814 157	2 473 405
1996	1 085 978	759 970	2 307 435
1997	1 007 389	705 784	2 141 466
1998	928 800	648 000	1 971 000
1999	852 484	597 410	1 812 367
2000	776 167	543 223	1 649 238
2001	699 851	489 037	1 486 110
2002	623 535	434 850	1 322 981
2003	547 219	380 663	1 159 852
2004	470 902	328 537	999 299
2005	164 768	272 289	546 322
2006	126 333	218 103	430 545
2007	87 898	163 916	314 767
2008	80 848	109 729	238 221
2009	73 798	55 542	161 676
2010	66 748	1 355	85 130
2011	59 699	0	74 623
2012	52 649	0	65 811
2013	45 599	0	56 999
2014	38 549	0	48 186
2015	37 228	0	46 535
2016	35 907	0	44 884
2017	49 848	0	62 310
2018	63 789	0	79 737
2019	63 789	0	79 737
2020	63 789	0	79 737

Notes:

BDt = Bone dry tonnes

a. Where no data was available, linear interpolation was used between data points. For the year 2019 and 2020, the 2018 value was carried forward.

b. Converted from bone-dry tonnes (BDt) to hydrated tonnes using a moisture content of 20%.

Table A3.6-8 Wood Waste Landfilled by Province (Hydrated Tonnes)

Year	NL	PE	NS	NB	QC	ON	MB	SK	AB	BC
1970–1990 ^a	49 702	674	50 587	32 527	418 671	285 928	21 592	89 629	472 427	1 883 451
1991	47 178	639	48 017	30 874	397 403	271 402	20 495	85 076	448 428	1 787 772
1992	44 682	606	45 477	29 241	376 380	257 045	19 411	80 575	424 705	1 693 195
1993	42 186	572	42 936	27 608	355 356	242 687	18 326	76 075	400 982	1 598 617
1994	39 690	538	40 396	25 974	334 332	228 329	17 242	71 574	377 259	1 504 040
1995	37 194	504	37 856	24 341	313 309	213 971	16 158	67 073	353 537	1 409 462
1996	34 699	470	35 316	22 708	292 285	199 613	15 074	62 572	329 814	1 314 885
1997	32 203	436	32 776	21 074	271 262	185 255	13 990	58 072	306 091	1 220 308
1998	7 884	0	21 681	65 043	601 155	165 564	7 884	17 739	329 157	754 893
1999	7 249	0	19 936	59 808	552 772	152 239	7 249	16 311	302 665	694 137
2000	6 597	0	18 142	54 425	503 018	138 536	6 597	14 843	275 423	631 658
2001	5 944	0	16 347	49 042	453 263	124 833	5 944	13 375	248 180	569 180
2002	5 292	0	14 553	43 658	403 509	111 130	5 292	11 907	220 938	506 702
2003	4 639	0	12 758	38 275	353 755	97 428	4 639	10 439	193 695	444 223
2004	9 993	0	9 993	0	39 972	39 972	9 993	59 958	179 874	649 544
2005	3 404	0	3 404	7 453	39 305	28 971	8 062	23 667	104 810	327 247
2006	2 726	0	2 726	5 714	30 603	22 680	6 298	18 846	82 460	258 491
2007	2 049	0	2 049	3 976	21 901	16 388	4 534	14 025	60 111	189 735
2008	1 372	0	1 372	3 657	18 092	13 022	3 657	9 822	46 056	141 172
2009	694	0	694	3 338	14 284	9 655	2 781	5 619	32 000	92 610
2010	17	0	17	3 019	10 475	6 289	1 904	1 416	17 945	44 047
2011	0	0	0	2 700	9 308	5 564	1 688	1 176	15 777	38 410
2012	0	0	0	2 381	8 209	4 907	1 488	1 037	13 914	33 874
2013	0	0	0	2 063	7 110	4 250	1 289	898	12 051	29 338
2014	0	0	0	1 685	8 354	2 289	1 067	280	10 428	24 084
2015	0	0	0	1 580	5 989	1 810	906	871	12 429	22 950
2016	0	0	0	1 488	5 544	1 731	1 154	331	12 474	22 161
2017	0	0	0	2 012	10 864	1 658	893	438	14 875	31 569
2018	0	0	0	3 227	14 651	2 797	1 408	449	19 431	37 774
2019	0	0	0	3 227	14 651	2 797	1 408	449	19 431	37 774
2020	0	0	0	3 227	14 651	2 797	1 408	449	19 431	37 774

Note:

a. Values for 1990 are used for 1970–1990.

A3.6.1.3.2. Model Parameters

Degradable Organic Carbon

It is assumed that all waste sent to private wood waste lots is composed entirely of wood. Therefore, the recommended 2006 IPCC Guidelines (IPCC, 2006) default DOC value for wood, i.e., 0.43, is used for all regions and time periods.

Fraction of Degradable Organic Carbon Which Decomposes

The 2019 IPCC Refinement (IPCC, 2019) recommended default value of 0.1 for less degradable organic carbon which decomposes (DOC_l) is used for the solid wood industry for all regions and time periods, while pulp and paper landfilled waste uses the IPCC 2006 default DOC_f value of 0.5.

Methane Correction Factor

The 2006 IPCC Guidelines (IPCC, 2006) recommended default MCF value of 0.8 for unmanaged deep landfill sites was selected, as it best represents industry practices.

Reaction Constant

The default decay rate constant (k) value of 0.03/year recommended by the National Council for Air and Stream Improvement Inc. for estimating the wood products industry's landfill CH₄ emissions was used for all regions and time frames (NCASI, 2003).

Fraction of landfill gas that is CH₄

The default fraction (F) of 0.5 recommended by the 2006 IPCC Guidelines (IPCC, 2006) is used for all time periods and regions.

Oxidation Factor

The 2006 IPCC Guidelines (IPCC, 2006) recommended default oxidation factor (OX) of 0.0 is used for all time periods and regions.

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Methane Recovery

It is assumed that no landfill gas capture technologies are used at private wood lots. Use of these sites is rapidly decreasing, and it is unlikely that facilities would invest in such infrastructure given the more popular practice of repurposing wood waste.

A3.6.2. Biological Treatment of Solid Waste (5.B)

The Biological Treatment of Solid Waste category consists of the following two emission sources: composting and anaerobic digestion.

A3.6.2.1. Composting (5.B.1)

The greenhouse gas emissions estimated from composting in Canada include CH₄ and N₂O. Since CO₂ emissions released by composting result from the decomposition of organic material from biomass sources, these emissions are not included in the national total.

A3.6.2.1.1. Methodology

A Tier 3 method is used to estimate emissions from composting. Feedstock-specific emission factors developed through an in-house literature review are applied to quantities of treated compost, as shown in Equation A3.6–7 and Equation A3.6–8. Emissions are calculated at a facility level and combined to create emissions estimates at provincial and national levels.

Equation A3.6–7 CH₄ Emissions from Composting

$$CH_4\text{ Emissions} = \sum_i (M_i \cdot EF_i) \cdot 10^{-3}$$

<i>CH₄ Emissions</i>	=	total CH ₄ emissions in inventory year, Gg CH ₄
<i>M_i</i>	=	mass of organic wet waste treated by type <i>i</i> , Gg
<i>EF</i>	=	emission factor for treatment <i>i</i> , g CH ₄ /kg waste treated by waste type
<i>i</i>	=	composting feedstock at facility <i>i</i>

Emission factors for various feedstocks include those for yard waste (1.72 g/kg), municipal solid waste (1.51 g/kg), biosolids/manure (3.54 g/kg) and a mixture of the aforementioned wastes co-composted (1.09 g/kg) based on wet weight (ECCC, 2020d).

Equation A3.6–8 N₂O Emissions from Composting

$$N_2O\text{ Emissions} = \sum_i (M_i \cdot EF_i) \cdot 10^{-3}$$

<i>N₂O Emissions</i>	=	total N ₂ O emissions in inventory year, Gg N ₂ O
<i>M_i</i>	=	mass of organic wet waste treated by type <i>i</i> , Gg
<i>EF</i>	=	emission factor for treatment <i>i</i> , g N ₂ O/kg waste treated by waste type
<i>i</i>	=	composting feedstock at facility <i>i</i>

Emission factors for various feedstocks include those for yard waste (0.25 g/kg), municipal solid waste (0.18 g/kg), biosolids/manure (0.18 g/kg) and a mixture of the aforementioned wastes co-composted (0.11 g/kg) based on wet weight (ECCC, 2020d).

A3.6.2.1.2. Data Sources

The activity data used to estimate CH₄ and N₂O emissions from composting are based on commercial/municipal facility-level information collected from industry surveys (from 1992 forward), technical reports, and facility websites. Home composting is not included in the Canadian inventory at this time due to lack of available data. To address the missing data years at the facility level, the last data point was carried forward to the next available data point, with the exception of the 1992 survey results being carried backward to develop a complete time series from 1990.

A3.6.2.2. Anaerobic Digestion at Biogas Facilities (5.B.2)

The greenhouse gas emissions estimated from anaerobic digestion of solid waste in Canada include CH₄. N₂O is considered to be negligible according to the 2006 IPCC Guidelines and is therefore not estimated for this sector. Since CO₂ emissions released by anaerobic digestion result from the decomposition of organic material from biomass sources, these emissions are not included in the national total.

A3.6.2.2.1. Methodology

Greenhouse gas emissions from anaerobic digestion of solid waste at biogas facilities are estimated for Canada using a Tier 3 method. The Tier 3 method includes determination of the CH₄ component of the biogas at the facility-level, a portion of which is lost through on-site leakages in the system. The loss from on-site leakages in the system is calculated at 2.1% of the CH₄ in the biogas produced. This value was developed from compiling losses found in primary literature and survey data from municipal, industrial and wastewater digesters (ECCC, 2020e). Losses from biogas upgrading and incomplete combustion are not included in on-site leakage loss. Losses from venting are not reported as they are considered sporadic in nature and are avoided as much as possible in Canada; it is believed these emissions are negligible. Emissions are calculated according to Equation A3.6–9.

Equation A3.6–9 CH₄ Emissions from Anaerobic Digestion

$$\text{CH}_4 \text{ Emissions} = \sum_i ((B_i \cdot M) \cdot EF) \cdot (D) \cdot 10^{-3}$$

CH₄ Emissions	=	total CH ₄ emissions in inventory year, Gg
<i>B_i</i>	=	biogas production by <i>i</i> , m ³
<i>D</i>	=	density of CH ₄ at normal temperature and pressure
<i>M</i>	=	Average CH ₄ content of biogas from inventory facilities
<i>EF</i>	=	emission factor for treatment <i>i</i> , as percentage of total CH ₄ in biogas produced that is lost through onsite leakages
<i>i</i>	=	facility <i>i</i>

A3.6.2.2.2. Data Sources

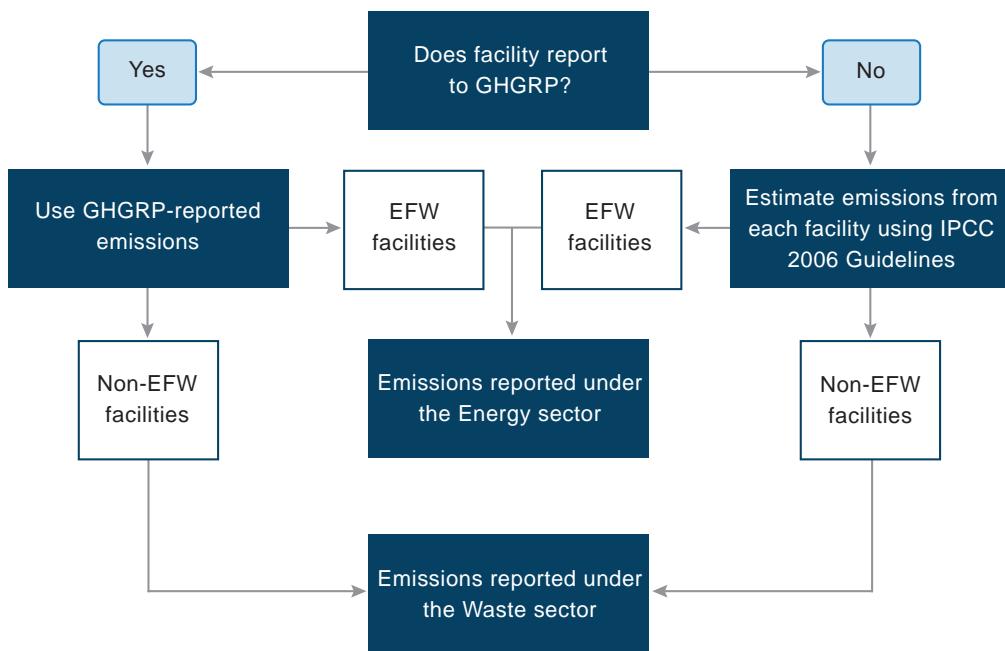
The activity data is based on facility level biogas production reported through in-house and industry based surveys. In the absence of facility reported data for biogas production, a conversion factor by feedstock type is used to generate biogas production from initial feedstock input. Only municipal and industrial anaerobic digestion facilities are reported under 5.B.2, whereas wastewater anaerobic digesters are reported under CRF category 5.D. On-farm anaerobic digesters are currently not included in our Canadian inventory, but will be considered in future inventories.

A3.6.3. Incineration and Open Burning of Waste (5.C)

Waste incineration is defined in the 2006 IPCC Guidelines as the combustion of solid and liquid waste in controlled incineration facilities. Incineration emissions in Canada come from MSW incineration, hazardous waste incineration, clinical waste incineration and sewage sludge incineration. Open burning of waste occurs mainly in rural areas and includes burning garbage in backyard barrels and/or open pits. This section of Annex 3 details the accounting methodologies that are used to describe the GHG emission estimates for these categories.

In keeping with the 2006 IPCC Guidelines (IPCC, 2006), only CO₂ emissions resulting from oxidation of carbon in waste of fossil origin (e.g., plastics, certain textiles, rubber, liquid solvents, and waste oil) are considered net emissions and are included in the national CO₂ emissions estimate. CO₂ emissions from combustion of biomass materials (e.g., paper, food and wood waste) contained in the waste are biogenic emissions and are not included in national total emission estimates.

Figure A3.6–3 Decision Tree for Collecting, Estimating and Reporting GHG Emissions from Incineration Facilities



Some facilities generate energy in the form of electricity and/or heat from waste incineration. These facilities are referred to as energy-from-waste (EFW) facilities. Other facilities simply incinerate waste for disposal purposes and are referred to as non-energy-from-waste (non-EFW) facilities. In accordance with the 2006 IPCC Guidelines, emissions from waste incineration with energy recovery are reported in the Energy sector, while emissions from waste incineration without energy recovery are reported in the Waste sector. The following section describes the methodology used for all incinerators, though final emissions are reported under the appropriate sector (Figure A3.6–3).

The Greenhouse Gas Reporting Program (GHGRP) has significant coverage of the incineration sector in more recent years. Over time, incineration practices have changed from many small facilities treating waste on site, to large specialized central facilities treating waste shipped in from across the provinces. Where GHGRP does not have coverage, facility-specific emission estimates were developed using the best available information. This bottom-up, facility-specific approach to developing emissions estimates was implemented for the MSW sector for Canada's 2019 National Inventory Report submission. New for this submission is that the other incineration sectors are calculated using the same approach, such that all incineration types are reported in a consistent manner.

Some facilities in Canada burn waste from multiple waste sources. For example, clinical waste is often burned alongside MSW waste. Emissions from facilities that treat more than one type of waste have been calculated according to the specific waste type but are reported under the facilities' primary waste sector. Therefore, if a facility treats small quantities of clinical waste alongside MSW, it is considered an MSW facility and the clinical waste emissions will be reported under MSW.

A3.6.3.1. Data Sources

Tonnage of Waste Incinerated

The total amount of waste incinerated is only directly used for facilities that do not report to the GHGRP. It is important to note that these data are also used to isolate the amount of waste landfilled in Canada from the amount of waste disposed of, as discussed in section A3.6.1.2.2. Therefore, even where a facility reports GHG emission totals to GHGRP, annual tonnage incinerated is still collected. The amount of waste incinerated at facilities across Canada is obtained through voluntary biennial surveys of incineration facilities conducted by ECCC. The survey has collected data every two years since 2008, with the most recent data collection occurring in the summer of 2020.

Supplemental data sources are used for facilities not included in the survey either due to non-response or because the facility closed before the first survey cycle in 2008. Tonnage is estimated using old reports (Sawell et al., 1996; Environment Canada 1999, 2003). Other sources include progress reports prepared by the Canadian Council of Ministers of the Environment on issues related to dioxins, furans and mercury emissions, as clinical waste incineration was formerly a major source of these pollutants (CCME 2006, 2007, 2010). A report on solid waste incineration in Canada prepared by A.J. Chandler & Associates Ltd. for Environment Canada (Environment Canada, 2003) was also used. Quantities of material incineration in Canada are found in Table A3.6–9.

Where the time series of tonnage incinerated is incomplete for the operational lifetime of a facility, the nearest data are carried forward or backward. Facilities in the clinical waste incineration sector are treated slightly differently as it used to be common practice to have small batch incinerators located at hospitals. Over time, provinces underwent mass closures of their small batch hospital incinerators and switched to shipping waste to central specialized facilities. Missing data points for these small hospital incinerators are estimated based on interpolation using provincial population numbers.

Contents of MSW waste incinerated include paper, glass, metal, plastic, food waste, yard waste, textiles, rubber, wood and other materials. The types of clinical waste incinerated in Canada include cytotoxic waste, human or animal anatomical waste and pharmaceutical waste (Stericycle, 2014). Hazardous waste incineration includes contaminated substrates such as soils, wood, metal and other material. The hazardous waste quantities may also include inorganic wastes such as aqueous solutions containing heavy metals, or wastes such as water-based urethanes, as opposed to solvent-based urethane wastes that have high fossil fuel carbon content. Sewage sludge incineration is the incineration of biosolids resulting from the processing of municipal sewage.

Table A3.6–9 **Estimated Tonnes of Waste Incinerated by Waste Source 1990–2020**

Year	Non-EFW Facilities				EFW Facilities
	MSW	Clinical Waste	Hazardous Waste	Sewage Sludge	
1990	126 573	3 196	100 762	128 402	1 004 353
1991	126 300	3 209	109 111	137 375	1 001 780
1992	127 834	3 225	117 879	144 575	1 178 827
1993	125 482	4 794	125 109	152 557	1 064 215
1994	126 968	4 804	142 050	168 795	885 648
1995	114 984	4 816	164 727	169 091	882 311
1996	116 501	4 823	146 125	187 196	900 594
1997	112 199	4 825	132 348	180 380	893 969
1998	105 753	2 899	155 511	179 186	892 174
1999	100 474	2 902	139 420	189 185	934 375
2000	100 318	2 989	168 379	187 889	898 831
2001	100 257	4 174	179 525	192 546	887 379
2002	100 078	4 298	184 845	206 450	902 813
2003	98 485	4 255	144 036	196 049	773 205
2004	86 844	4 855	161 891	195 525	793 713
2005	73 316	5 332	160 688	192 699	786 197
2006	73 665	5 689	147 775	196 287	797 250
2007	73 218	5 572	134 878	195 058	755 871
2008	70 085	3 212	147 528	190 919	764 102
2009	52 893	3 359	133 356	192 681	751 868
2010	42 343	2 864	137 830	193 360	699 119
2011	30 652	3 394	130 319	207 415	788 144
2012	34 607	3 034	84 785	202 062	782 115
2013	27 000	3 250	90 090	201 486	780 712
2014	22 450	3 226	107 810	209 675	760 124
2015	19 707	3 093	122 911	217 696	808 872
2016	22 140	3 344	124 695	205 730	863 445
2017	23 334	3 451	124 747	206 047	860 963
2018	22 915	3 374	121 105	209 105	869 729
2019	22 915	3 381	118 757	218 722	868 244
2020	22 915	3 354	118 757	218 722	868 244

A3.6.3.1.1. Methodology

Emission estimates are compiled at a facility level, and a distinction is made between EFW facilities and non-EFW facilities. Where GHGRP emissions are available, they are used. Where GHGRP emissions are not available, facility-specific emissions are estimated using methodologies prescribed in the 2006 IPCC Guidelines (IPCC, 2006).

Facilities Reporting to the GHGRP

GHGRP facility data are available annually from 2004 onwards, though most MSW incinerators started reporting in 2009. Where facilities were operating before 2009, the emissions time series was completed by assuming that tonnage incinerated is directly correlated with emissions. The “Surrogate Data” method prescribed in Volume 1, Chapter 5.3.3.2, of the 2006 IPCC Guidelines (IPCC, 2006) is used to complete the time series of emissions using annual tonnage incinerated by the facility, obtained through surveys and/or reports, as well as GHGRP data for all years for which such data are available.

Note that GHGRP reporting guidelines require that facility-reported CO₂ emissions are derived only from wastes of fossil origin (e.g., plastics, certain textiles, rubber, liquid solvents and waste oil). CO₂ from the biogenic portion of waste (e.g., food, wood, garden waste) are excluded from emissions totals.

Non-reporting Facilities

There are a large number of incinerators that either closed before the GHGRP was launched or operated below the reporting threshold. Many of these facilities that are classified under MSW were small incinerators across Newfoundland and Labrador, but also include some larger facilities in Ontario, Quebec, British Columbia and Alberta. Estimates for these facilities were developed using the 2006 IPCC Guidelines and the best available parameters for each facility.

CO₂ Emissions

Emissions of CO₂ from MSW incineration are estimated using the mass-balance approach prescribed by Equation A3.6–10, equivalent to Equation 5.2 in the 2006 IPCC Guidelines.

Where available, facility-specific waste characterization data was used to determine the different materials of waste in the waste incinerated (factor “WF_j” in Equation A3.6–10). Where facility-specific characterization data were not available, provincial characterization data were taken from Environment Canada (1996). This report contains waste characterization data for EFW and non-EFW streams of waste incineration. Table A3.6–10 contains the default factors from the 2006 IPCC Guidelines that were used to determine the CO₂ emissions from each waste type incinerated. The default values of 60% for total carbon (% of dry weight) and 40% for fossil carbon as a percentage of total carbon was used for clinical waste, and a carbon content of 50% and fossil carbon of 90% as a percentage of total carbon were used for hazardous waste. These values come from the 2006 IPCC Guidelines (IPCC, 2006).

A default factor of 1 is used as the oxidation factor (OF) for all waste types and facilities.

Equation A3.6–10 (modified from 2006 IPCC Guidelines Equation 5.2)

$$CO_2 \text{ Emissions} = \text{Waste} \times \sum(WF_j \times dm_j \times CF_j \times FCF_j \times OF) \times 44/12$$

<i>CO₂ Emissions</i>	=	CO ₂ emissions in inventory year
<i>Waste</i>	=	total amount of waste incinerated
<i>J</i>	=	component of MSW incinerated, such as paper/cardboard, textiles, food waste, wood, plastic, garden waste, plastics, metal, glass, etc.
<i>WF_j</i>	=	fraction of waste type/material <i>j</i> in total MSW waste incinerated
<i>dm_j</i>	=	dry matter content of component <i>j</i> in total MSW waste incinerated
<i>CF_j</i>	=	fraction of carbon in the dry matter (i.e., carbon content) of component <i>j</i>
<i>FCF_j</i>	=	fraction of fossil carbon in the total carbon of component <i>j</i>
<i>OF</i>	=	oxidation factor
<i>44/12</i>	=	conversion factor from C to CO ₂

Table A3.6–10 Default Factors Used in Equation A3.6–12 to Determine CO₂ from Incineration

Waste Type	Dry Matter Content (% Wet Weight)	Total Carbon (% Dry Weight)	Fossil Carbon (% Total Carbon)
Paper	0.90	0.46	0.01
Textiles	0.82	0.59	0.20
Food	0.40	0.38	0.00
Wood	0.85	0.50	0.00
Yard	0.40	0.70	0.10
Nappies	0.40	0.70	0.10
Rubber	0.82	0.59	0.20
Plastic	1.00	0.75	1.00
Metal	1.00	0.00	0.00
Glass	1.00	0.00	0.00
MSW Other ^a	1.00	0.34	0.35
Clinical	0.65	0.60	0.40
Hazardous Waste	1.00	0.50	0.90
Sewage Sludge	1.00	0.45	0.00
Organics ^b	0.40	0.44	0.00
Inorganics	1.00	0.03	1.00
Fossil Liquid Waste	1.00	0.80	1.00
Solvents	1.00	0.80	0.80
Industrial Wood	0.85	0.41	0.01
Industrial Sludge	1.00	0.50	0.90
Other Industrial Waste	1.00	0.50	0.90

Notes:

- a. Many facilities report "other" waste, without identifying what it includes. Therefore, an average of textiles, food, garden, rubber and inert waste are used in these cases. Note that paper and plastic are always characterized separately and so are not incorporated into the "other" parameter.
- b. In cases where facility waste characterization includes organics in general, the organics parameters are used. If the facility distinguishes between food and garden waste, those specific factors are used.

CH₄ Emissions

CH₄ emissions from incineration are determined for each facility using default emission factors from the 2006 IPCC Guidelines. Emission factors are multiplied by the total annual waste incinerated at the facility (Equation A3.6–11). Emission factors vary depending on how the incinerator is fed (continuous, semi-continuous, or batch-type incineration) and on the incinerator type (stoker vs fluidized bed). The most appropriate emission factor was chosen for each facility. In the absence of IPCC default emission factor values for hazardous waste, CH₄ emission factors were derived using data from one hazardous waste incineration facility that had provided total emissions based on direct measurements taken in 2007. The site emitted 0.03 tonnes of N₂O and burned 177 tonnes of hazardous waste. Therefore, the emission factor 169 g CH₄/tonnes of hazardous waste was determined. CH₄ emissions from sewage sludge are derived using the emission factor of 9.7 kg/kt of total dried solids for fluidized bed sewage incinerators obtained from the U.S. Environmental Protection Agency (U.S. EPA, 1995). CH₄ emissions from sewage sludge incineration are dependent on the amount of dried solids incinerated. To calculate the CH₄ emissions, the amount of dried solids incinerated is multiplied by an appropriate emission factor.

Equation A3.6–11 (modified from 2006 IPCC Guidelines Equation 5.4)

$$\text{CH}_4 \text{ Emissions} = \sum(W_f \times EF_f)$$

- CH₄ Emissions** = CH₄ emissions from waste incineration in inventory year
W_f = total amount of waste incinerated at facility *f*
EF_f = emission factor most appropriate for facility *f*

N₂O Emissions

As with CH₄ emissions, N₂O emissions from incineration are determined for each facility using default emission factors from the 2006 IPCC Guidelines. Emission factors are multiplied by the total annual waste incinerated at the facility (Equation A3.6–12). Emission factors vary depending on the feed type of the incinerator (continuous, semi-continuous and batch-type incineration). Solid waste default emission factors were used in accordance with the IPCC Good Practice Guidance (IPCC, 2000) as no clinical-waste-specific values are provided. The N₂O emissions for a given site were therefore calculated using the stoker default emission factors for continuous incineration (50 g N₂O/t waste incinerated) and batch-type incineration (60 g N₂O/t waste incinerated) provided in IPCC (2006). Emissions of N₂O from sewage sludge incineration have been updated using the IPCC 2006 Guidelines default emission factor 0.99 kg/t of dried sewage sludge incinerated (IPCC, 2006). Hazardous waste N₂O emission factors were derived using the same methodology as CH₄. Direct measurements of 0.56 tonnes N₂O for 177 tonnes of hazardous waste burned in 2007 result in an emission factor of 3164 gN₂O/tonne HW.

Note that although the 2006 IPCC Guidelines provide a MSW incinerator emission factor for open burning, it is assumed that no MSW incineration facilities in Canada practice open burning. The most appropriate emission factor was chosen for each facility.

Equation A3.6–12 (modified from 2006 IPCC Guidelines Equation 5.5)

$$N_2O \text{ Emissions} = \sum(W_f \times EF_f)$$

N₂O Emissions = N₂O emissions from MSW incineration in inventory year

W_f = total amount of MSW incinerated at facility f

EF_f = emission factor most appropriate for facility f

The full list of emission factors used can be found in Table A3.6–11.

Table A3.6–11 Default CH₄ and N₂O Emission Factors for Incineration Facilities

Waste Type	Feed Type	Incinerator Type	CH ₄ Emission Factor	N ₂ O Emission Factor	Units
Municipal Solid Waste	Continuous	Stoker	0.20	50.00	g/t
Municipal Solid Waste	Continuous	Fluidized Bed	0.00	50.00	g/t
Municipal Solid Waste	Semi Continuous	Stoker	6.00	50.00	g/t
Municipal Solid Waste	Semi Continuous	Fluidized Bed	188.00	50.00	g/t
Municipal Solid Waste	Batch	Stoker	60.00	60.00	g/t
Municipal Solid Waste	Batch	Fluidized Bed	237.00	60.00	g/t
Hazardous Waste	Continuous	Stoker	169.49	3 163.84	g/t
Hazardous Waste	Batch	Stoker	169.49	3 163.84	g/t
Sewage Sludge	Continuous	Fluidized Bed	9.70	990.00	g/t
Sewage Sludge	Continuous	Stoker	9.70	990.00	g/t
Clinical Waste	Continuous	Stoker	0.20	50.00	g/t
Clinical Waste	Batch	Stoker	60.00	60.00	g/t
Clinical Waste	Semi Continuous	Stoker	0.20	50.00	g/t
Other Sludge	Continuous	Stoker	0.20	450.00	g/t
Other Sludge	Batch	Stoker	60.00	450.00	g/t
Fossil Liquid Waste	Continuous	Stoker	0.20	100.00	g/t
Fossil Liquid Waste	Batch	Stoker	60.00	100.00	g/t
Industrial Waste	Continuous	Stoker	0.20	50.00	g/t
Industrial Waste	Continuous	Fluidized Bed	0.00	50.00	g/t
Industrial Waste	Semi Continuous	Stoker	6.00	50.00	g/t
Industrial Waste	Semi Continuous	Fluidized Bed	188.00	50.00	g/t
Industrial Waste	Batch	Stoker	60.00	60.00	g/t
Industrial Waste	Batch	Fluidized Bed	237.00	60.00	g/t

Table A3.6–12 National CO₂ eq Emissions from Incineration (1990–2020)

Year	Non-EFW Facilities				EFW Facilities MSW
	MSW	Clinical Waste	Hazardous Waste	Sewage Sludge	
1990	41	2	191	39	352
1991	41	2	202	42	352
1992	41	2	215	44	419
1993	40	3	214	46	386
1994	40	3	243	51	333
1995	37	3	279	51	331
1996	38	3	250	56	339
1997	36	3	227	54	331
1998	34	2	258	54	332
1999	33	2	256	57	347
2000	33	2	275	57	337
2001	33	3	288	58	332
2002	33	3	266	62	336
2003	33	3	268	59	294
2004	29	4	262	59	300
2005	23	4	262	58	298
2006	23	4	236	59	301
2007	23	4	241	59	286
2008	23	3	253	57	289
2009	18	4	209	58	285
2010	15	3	229	58	262
2011	11	3	226	62	289
2012	12	3	99	61	344
2013	10	4	105	73	337
2014	8	4	83	79	297
2015	7	3	110	76	375
2016	8	4	115	77	414
2017	8	5	114	64	395
2018	8	5	100	67	394
2019	8	5	94	70	399
2020	8	5	86	66	458

Total Emissions

Table A3.6–12 summarizes emissions from EFW and non-EFW facilities. The EFW emissions are reported under the Energy sector, while the non-EFW emissions are reported under the Waste sector.

A3.6.3.2. Open Burning of Waste (5.C.2)

Canada does not currently estimate GHG emissions from open burning of waste. While open burning at landfills is banned by regulation in most provinces and territories, there is anecdotal evidence that some open burning still occurs in rural areas of the country. However, this is a minor source of emissions relative to other activities. The likely level of emissions from open burning of MSW in Canada (as estimated for 2010) was nearly 100 kt or 0.015% of total national emissions. This is less than 0.05% of total emissions and less than the 500 kt threshold as specified in paragraph 37(b) of the UNFCCC Annex I Inventory Reporting guidelines. As this emissions value can be considered representative for all years, this source can be considered insignificant.

A3.6.4. Emissions from Wastewater Treatment and Discharge (5.D)

The emissions estimates for the Wastewater Treatment and Discharge category includes CO₂, CH₄ and N₂O emissions resulting from transformation of organics and nutrients in wastewater systems; however, biogenic CO₂ emissions are not included in totals for this sector because these emissions are considered to be of biogenic origin grown in the same year as emissions occur (and are thus covered under the AFOLU sectors).

CH₄ emissions occur from the treatment of municipal and industrial wastewater, from anaerobic digestion of sludge on-site at wastewater treatment facilities and from the emission of organics remaining in wastewater effluent are estimated in accordance with the methods provided in the 2006 IPCC Guidelines and 2019 Refinement using Tier-2 country-specific

factors. N_2O emissions are currently estimated as a function of the total nitrogen in wastewater in accordance with the methods described in the 2006 IPCC Guidelines and 2019 Refinement. Estimates of N_2O emission totals are dependent of the treatment technology used.

Emissions from municipal wastewater treatment are determined on a per capita basis. The per capita organics loading to wastewater and the population served by treatment type are the primary activity data for CH_4 emissions. Nitrogen loading to wastewater, estimated from per capita protein consumption, is the primary activity data for N_2O emissions.

Most wastewater treatment in Canada occurs at centralized municipal wastewater treatment plants (78% in 1990, 83% in 2019), which receive influent from domestic, commercial and industrial users. There are some coastal municipalities that collect and discharge untreated wastewater to sea. Many Canadians in rural and remote areas, but also in portions of urban centres, use private or communal septic systems for wastewater treatment. Larger industries treat or pre-treat their wastewater on-site and are considered separately from municipal wastewater treatment facilities in the Industrial On-Site Wastewater Treatment category, section A3.6.4.2.

A3.6.4.1. Municipal Wastewater Treatment/Discharge – CH_4

Emissions estimates for municipal wastewater treatment facilities are calculated using the Tier 2 methods provided in the 2006 IPCC Guidelines and 2019 Refinement, with country-specific factors (IPCC, 2006, 2019). The 2019 Refinement provides updated emission factors and methods for estimating emissions from receiving water bodies.

CH_4 emissions estimates are based on population-based organic loadings, treatment technology used and receiving water-body characteristics (Figure A3.6–4: Diagram of Wastewater Organics). CH_4 emissions occur from microbial activity under anaerobic condition that occurs during treatment, anaerobic digestion of sludge, and the receiving water body.

The treatment technology used influences the emissions from treatment, the removal of organics as sludge and the quantity of organics remaining in the effluent (which then contributes to emissions from the receiving water bodies). The first-step in estimating CH_4 emission from wastewater is determining the population using each type of treatment technology.

Methane emissions from wastewater treatment facilities occur at three distinct steps (Figure A3.6–4):

- Wastewater treatment
- Anaerobic digestion of sludge
- Microbial activity of organics that were discharged to receiving water body

The organics entering the wastewater stream (activity data) are converted to CH_4 (or CO_2) by microbial activity at each of these three steps. The emissions from the wastewater treatment process and the organics removed as sludge or passing to the receiving body with the effluent are a function of the treatment technology.

The total CH_4 emissions from wastewater facilities for each province or territory can be determined from the sum of emissions from each of the three steps, as shown in Equation A3.6–13. National emissions are the sum of all provincial and territorial emissions.

Equation A3.6–13

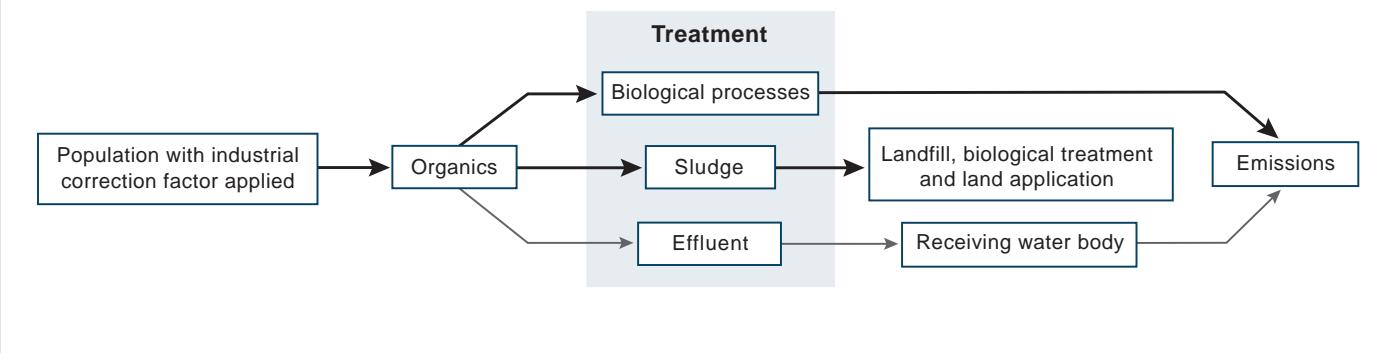
$$\text{CH}_4 = \text{CH}_4_{Treatment} + \text{CH}_4_{AD} + \text{CH}_4_{Receiving water body}$$

CH_4	=	CH_4 emissions from wastewater, for province, p
$\text{CH}_4_{Treatment}$	=	CH_4 emissions from the process of wastewater treatment (tonne CH_4)
CH_4_{AD}	=	CH_4 emissions from anaerobic digestion of sludge on-site at wastewater treatment facilities (tonne CH_4)
$\text{CH}_4_{Receiving water body}$	=	CH_4 emissions from the wastewater discharged to receiving water bodies (tonne CH_4)

Methodology

Emissions are ultimately a function of population and treatment technology used. The organic load—the mass of organic material introduced to wastewater—is a function of the population served. The treatment technology to which a wastewater treatment system is connected (if any) dictates the degree of emissions from the treatment process, the amount of organics removed as sludge and the amount of organics remaining in the wastewater effluents. The organics remaining in the effluents also contribute to CH_4 emissions (IPCC, 2019). The organics removed as sludge are sometimes processed in anaerobic digesters on-site at the wastewater treatment facilities. In these cases, CH_4 emissions from the anaerobic digestion are included in the wastewater totals.

Figure A3.6–4 Diagram of Wastewater Organics Flow



Organics removed as sludge (after any reductions from on-site anaerobic digestion) may then become inputs for accounting and emissions calculations in other sections, including Biological Treatment of Waste (section A3.6.2), Solid Waste Disposal (Landfills) (section A3.6.1), Incineration (section A3.6.3). Sewage sludge accounting—determining the amounts transferred to each of the aforementioned fates or sections—is discussed in this section.

Wastewater system is the term used to denote a sewershed or wastewater collection system. It does not necessarily have a wastewater treatment facility. In some cases, wastewater is collected but discharged to sea. Treatment systems may also employ more than one type of treatment technology, such as different kinds of lagoons cells run in series or in parallel.

Emissions from Wastewater Treatment

Methane emissions are estimated for each province based on organics loading to wastewater, organics removed as sludge and treatment-technology-specific emission factors, as shown in Equation A3.6–14.

Equation A3.6–14

$$CH_4 \text{ Treatment} = \sum_t [EF_{CH_4,t} \times (OrganicLoad_t - OrganicsRemovedAsSludge_t)]$$

$CH_4 \text{ Treatment}$	=	CH_4 emissions from wastewater treatment, tonne CH_4
t	=	treatment technology type or category (e.g., facultative lagoon)
$EF_{CH_4,t}$	=	CH_4 emission factor for wastewater treatment technology of type t , tonne CH_4 /tonne BOD_5
$OrganicLoad_t$	=	organic load to the wastewater treatment/discharge systems of type t , tonne BOD_5
$Organics Removed As Sludge_t$	=	the organics that are removed from wastewater as sludge, measured as tonne BOD_5

Emission Factor

The emission factor for wastewater treatment and discharge is a function of the theoretical maximum CH_4 production capacity (B_0) for wastewater and a treatment technology-specific CH_4 correction factor (MCF), as shown in Equation A3.6–15 and Table A3.6–13. The maximum CH_4 producing capacity was determined to be 0.36 kg CH_4 per kg BOD_5 by AECOM (2011). The MCF is the fraction of the potential CH_4 that is produced by each treatment type and ranges from 0 to 1 (IPCC, 2006), depending on the treatment system type.

Equation A3.6–15

$$EF_{CH_4,t} = B_0 \times MCF$$

$EF_{CH_4,t}$	=	emission factor for treatment type t , tonne CH_4 /tonne BOD_5
B_0	=	theoretical maximum CH_4 producing capacity, tonne CH_4 /tonne BOD_5
MCF	=	methane correction factor for treatment type t , fraction

Table A3.6–13 Emission Factors for CH₄ from Wastewater Treatment and Discharge

Treatment Category	MCF	EF	Source: MCF	BOD ₅ Removal Efficiency	Source: BOD ₅ Removal Efficiency	Sludge BOD ₅ per BOD ₅ Removed from Wastewater	Source: Sludge BOD ₅ per BOD ₅ Removed from Wastewater
No Treatment	0.1	0.036	IPCC (2006)	0	IPCC (2019)	0	
Primary	0.018	0.0036	IPCC (2019)	0.4	IPCC (2019)	1	Envirosim (2019), Table 3
Aerobic Lagoon	0	0	IPCC (2006)	0.85	ECCC Internal Analysis	0.01	Envirosim (2019), Table 6
Anaerobic Lagoon	0.8	0.288	IPCC (2006)	0.85	ECCC Internal Analysis	0.02	Envirosim (2019), Table 6
Facultative Lagoon	0.2	0.072	IPCC (2006)	0.85	ECCC Internal Analysis	0.01	Envirosim (2019), Table 6
Other / Unspecified Lagoon	0.2	0.072	IPCC (2006)	0.85	ECCC Internal Analysis	0.01	Envirosim (2019), Table 6
Secondary Anaerobic	0.8	0.288	IPCC (2006)	0.85	ECCC Internal Analysis	0.46	Modeling as Secondary Aerobic
Secondary Activated Sludge	0.01	0.0036	IPCC (2019)	0.95	IPCC (2019)	0.46	Envirosim (2019), Table 2, Secondary with Primary & Nitrification
Trickling Filter	0.01	0.0036	IPCC (2019)	0.85	ECCC Internal Analysis	0.6	Envirosim (2019), Table 5
Trickling Filter – High Rate	0.01	0.0036	IPCC (2019)	0.85	ECCC Internal Analysis	0.75	Envirosim (2019), Table 5
Rotating Biological Contactor	0.01	0.0036	IPCC (2019)	0.85	ECCC Internal Analysis	0.23	Surampalli and Baumann (1995)
Sequencing Batch Reactor	0.05	0.018	Taseli (2018)	0.9	Literature Review	0.46	Assuming similar to Secondary Activated Sludge. See Mahvi (2008)
Secondary Biofiltration	0.018	0.0036	IPCC (2019)	0.95	Literature Review	0.46	Assuming similar to Secondary Activated Sludge
Secondary with Biological Nutrient Removal	0.018	0.0036	IPCC (2019)	0.98	Literature Review / IPCC (2019) / Envirosim (2019) Assuming primary treatment included	0.46	Envirosim (2019), Table 2, Secondary with Primary & Nitrification
Septic	0.5	0.18	IPCC (2006)	1	Assuming dispersal field	0.5	IPCC (2019), Equation 6.3
Septic with Marine Outfall	0.5	0.18	IPCC (2006)	0.625	IPCC (2019), Table 6.6B	0.5	IPCC (2019), Equation 6.3
Wetland	0.17	0.0612	IPCC (2014) Wetland Supplement	0.975	Estimate	0	Assuming no dredging
Other / Unknown	0.2	0.072	Modeling as facultative lagoon	0.85	Modeling as facultative lagoon	0.01	Modelling as facultative lagoon

Organic Load

Emissions of CH₄ from municipal wastewater treatment systems are determined based on the organic loading to wastewater, by province (measured as biogeochemical oxygen demand, 5-day test, or BOD₅). The organic loading is determined from the per capita organics loading rate (BOD₅/capita/day) of 0.06 kg/person/day, and an industrial and commercial input correction factor of 1.25 (IPCC, 2006).

The total annual organic loading of each type of wastewater treatment technology in a province is calculated as shown in Equation A3.6–16.

Equation A3.6–16

$$\text{OrganicLoad}_t = \text{Pop}_t \times \text{IndCor} \times \text{PerCapBOD}_5 \times 365 \times 0.001$$

- OrganicLoad_t = annual organic load to the wastewater treatment systems of type *t*, tonne BOD₅
- Pop_t = population using (connected to) wastewater systems of technology type *t*
- IndCor = correction factor for industrial and commercial inputs to municipal wastewater, with value of 1.25 (IPCC, 2006)
- PerCapBOD_5 = per capita organic loading to the wastewater system, kg BOD₅/capita/day
- 365 = conversion from day to year
- 0.001 = conversion from kg BOD₅ to tonne BOD₅

Population Using Each Treatment Technology, By Province

There are over 3800 municipal wastewater treatment or discharge systems (wastewater system) in Canada. On top of that, much of the population uses private septic systems.

The total population using each treatment technology of each province can be determined by summing the number of people served by (connected to) each wastewater system (i.e., sewershed or facility) having each type of treatment. However, few wastewater treatment systems have direct measures of the number of people that they serve. Instead, the population served by each wastewater system must be estimated.

To estimate the population served by each facility, a geographic approach is taken:

1. Map population in each census metropolitan area (CMA) and each census division (CD), excluding overlapping areas with CMA, from 1990 onward, taking account of changing geographic boundaries with each census (Statistics Canada census population from 1991, 1996, 2001, 2006, 2011, 2016 censuses; Statistics Canada census administrative area boundaries [shapefiles or geodatabases] from 1996, 2016 and 2016 censuses).
2. Determine population in each region connected to municipal wastewater treatment systems and population using private or communal septic systems.
3. Distribute the CMA or CD population that discharges to municipal sewer systems between the wastewater treatment systems in that region according to the relative volume of wastewater that the systems process in a year. For example, a facility that treats 30% of the total annual wastewater of a CMA in a given year is assumed to serve 30% of the population of that CMA that is connected to the municipal sewer systems in that year.

The total population using each treatment technology for each province in each year is determined by summing the population of the wastewater treatment system having that technology, according to Equation A3.6–17.

Equation A3.6–17

$$\text{Population}_{\text{Using System}_t} = \sum_{i,t} \frac{\text{Volume Treated}_{i,t}}{\text{Total Volume Treated}_{\text{region}}} * \text{Population}_{\text{mun sewer, region}}$$

<i>Population_Using_System_t</i>	=	the estimated population served by the municipal wastewater treatment system of type <i>t</i>
<i>VolumeTreated_{i,t}</i>	=	the volume of wastewater treated by, or discharged from, facility <i>i</i>
<i>region</i>	=	the region (census metropolitan area or census division) in which system <i>i</i> is located (note: census geography boundaries change over time)
<i>TotalVolumeTreated_{region}</i>	=	the total volume of wastewater treated by all municipal wastewater systems in the region in which system <i>i</i> is located.
<i>Population_{mun_sewer,region}</i>	=	the population of the region in which system <i>i</i> is located in that live in residences connected to municipal sewer systems (as opposed to private septic systems)

The population discharging their wastewater to municipal sewer systems versus those discharging to private or small communal septic systems is determined from an analysis of the Households and Environment Survey (Statistics Canada. No date [c]). The septic versus sewer use can only be determined at the spatial resolution of census metropolitan area and “the rest of the province.” In other words, all census divisions in a province are treated as one for determining septic or municipal treatment use.

The volume of wastewater discharged (volume treated) from most (>2500) wastewater treatment systems in Canada and the treatment technology used are reported through the Effluent Regulatory Reporting Information System (ERRIS) under the *Wastewater Systems Effluent Regulations* of the *Fisheries Act* (Canada, 2012). Records from this source begin in 2013. To complete the time series and fill any data gaps, the reported volumes, treatment technology and details of facility construction, upgrade and decommissioning were also gathered from older national inventories, provincial inventories and reports, annual reports of treatment facilities, municipal websites, engineering reports, scholarly articles, news articles and other available sources. Notable data sources, in addition to data gathered through ERRIS, include the national inventory of municipal waterworks and wastewater systems in Canada, 1996 (Minister of Supply and Services Canada, 1987), the Government of Quebec (Québec, 2003, 2005, 2013), the Ontario Ministry of the Environment (1985) and the Newfoundland Water Resources Portal (n.d.).

The data for septic use (and municipal wastewater system use), and volumes treated are not available for every year. Gaps in the time series of provincial and census metropolitan area septic use are linearly interpolated and extrapolated by holding values constant. Gaps in the time series of wastewater volumes are linearly interpolated and extrapolated by scaling from the nearest known value according to regional population changes.

Many small systems have no reported volumes for any year (1426 systems). This may be because the systems are below the mandatory reporting threshold of 100 m³/day for the *Wastewater System Effluent Regulations* or because they closed before the regulations came into effect in 2014. These systems are given a token treatment volume of 50 m³/day (which corresponds to populations of approximately 50 to 200 people, varying by region). Even with token volumes assigned, these ‘small’ systems represent a negligible contribution to the overall volume of wastewater treated in Canada.

The treatment technology of a given wastewater system is extrapolated by holding the earliest and last known technology constant. When the treatment technology of a given system has changed over time and the precise year of change is unknown, the technology type is interpolated by carrying the earlier technology forward until the first recorded year of the newer technology (i.e., it is assumed that the first instance or record of the newer technology likely corresponds to the year of upgrade).

The estimated population connected to each treatment technology type, by province and territory is shown in Figure A3.6–5. Percentages of Canadian population connected to the wastewater systems of each treatment technology are shown in Table A3.6–14.

Figure A3.6–5 Population Served by Each Treatment Technology, by Province and Territory

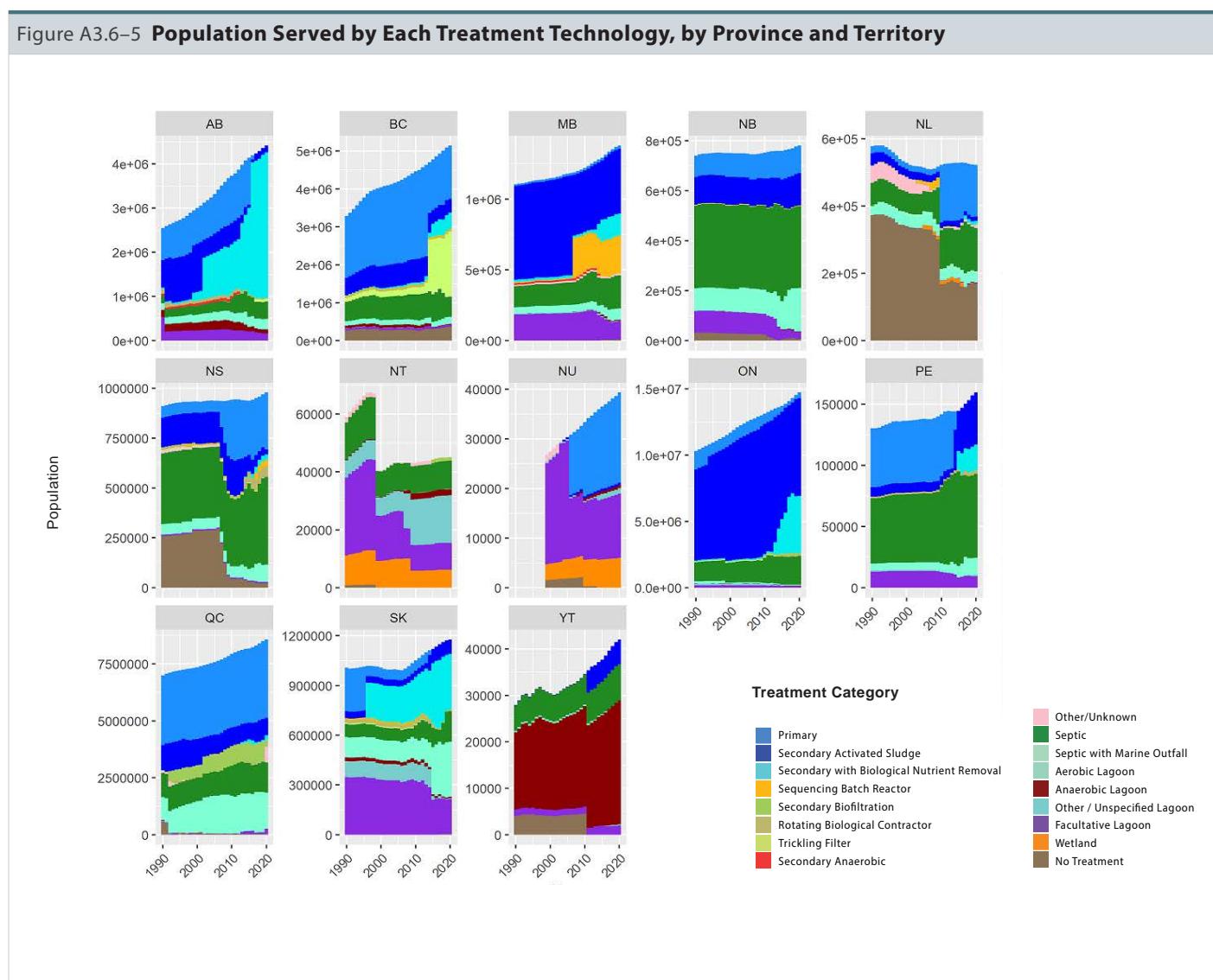


Table A3.6–14 Percentage of Canadian Population Using Each Wastewater Treatment Technology

Treatment Category	Year						
	1990	1995	2000	2005	2010	2015	2020
Aerobic Lagoon	6.48	6.78	6.91	7.56	7.19	7.39	7.4
Anaerobic Lagoon	1.09	1.11	1.06	1.04	0.97	0.51	0.45
Facultative Lagoon	5.26	4.02	3.81	3.69	3.37	2.65	2.63
No Treatment	5.51	3.37	3.14	3.04	1.61	1.56	1.6
Other / Unknown	0.56	0.37	0.26	0.16	0.09	0.17	1.96
Other / Unspecified Lagoon	0.91	0.88	0.81	0.76	0.73	0.21	0.08
Primary	26.27	24.47	23.54	23.24	23.82	18.68	15.44
Rotating Biological Contactor	0.64	0.43	0.39	0.39	0.39	0.57	0.54
Secondary Activated Sludge	36.35	39.89	41	38.02	36.83	28.04	24.8
Secondary Anaerobic	0.21	0.21	0.22	0.22	0.21		
Secondary Biofiltration	0.01	1.87	1.71	2.34	2.58	2.68	0.75
Secondary with Biological Nutrient Removal	0.51	0.53	1.8	4.23	4.54	15.62	23.29
Septic	15.24	15.08	14.34	14.18	15.75	16.77	15.3
Septic with Marine Outfall	0.01	0.02	0.02	0.02	0.02	0.02	0.01
Sequencing Batch Reactor	0.21	0.22	0.22	0.33	1.07	1.01	1.07
Trickling Filter	0.7	0.66	0.72	0.69	0.76	4.05	4.63
Wetland	0.04	0.1	0.04	0.08	0.07	0.08	0.04

Note: Values may not add up to 100% due to rounding.

Organics Removed As Sludge

Sludge removal is not measured directly at all facilities across Canada and is therefore estimated by modelling it as a function of the treatment technology. In addition to treatment technology, there are many factors at play that will impact sludge removal, from operating temperatures to flow rates. However, on aggregate, and using “typical” operating practices and configurations, average sludge removals across the various treatment technologies in use in Canada can be estimated.

Organics removed from the wastewater as sludge, measured as units of BOD₅, are estimated according to Equation A3.6–18 and Equation A3.6–19, using parameters shown in Table A3.6–13.

Equation A3.6–18

$$\text{Organics_Removed_Via_Treatment}_t = \text{OrganicLoading}_t \times \text{BOD5_Removal_Efficiency}_t$$

- Organics_Removed_Via_Treatment* = total amount of organics (measured as BOD₅) removed from the wastewater, for treatment type *t*, tonne BOD₅
OrganicLoading_t = organic load to the wastewater treatment/discharge system, tonne BOD₅
BOD Removal Efficiency_t = average or typical efficiency of wastewater treatment technology, in Canada, at removing BOD₅ from wastewater (Table A3.6–13), fraction

Equation A3.6–19

$$\text{BOD5_Removed_As_Sludge}_t = \text{Organics_Removed_Via_Treatment}_t \times \text{SludgeBOD5_Per_BOD5_Removed}_t$$

- BOD_Removed_As_Sludge_t* = quantity of BOD₅ (t BOD₅) removed from the wastewater as sludge for treatment type *t*.
Organics_Removed_Via_Treatment_t = total amount of organics (measured as BOD₅) removed from the wastewater, for treatment type *t*.
SludgeBOD_Per_BOD_Removed_t = treatment technology-specific factor for amount of BOD₅ removed from wastewater as sludge per unit of BOD₅ removed from wastewater during treatment (not 1:1 because of other BOD₅ removal mechanisms such as emissions)

Emissions from Receiving Water Body (Organics Remaining in Effluent)

Canada uses a Tier 1 approach from the 2019 IPCC Refinement (IPCC, 2019). The emissions are calculated using Equation A3.6–20 to Equation A3.6–22. The receiving water body types are unknown, but a country specific value for B_0 (of 0.36) is used to determine the emission factor, of 0.0396 kg CH₄ per kg BOD₅ in wastewater effluent discharged to receiving water bodies.

Equation A3.6–20

CH_4 receiving water body = EF_{CH_4} receiving water body × $OrganicLoad_{effluent}$	
CH_4 receiving water body, p	= CH ₄ emissions from receiving water bodies in province p
EF_{CH_4} receiving water body	= CH ₄ emission factor for wastewater treatment technology, tonne CH ₄ / tonne BOD ₅
$OrganicLoad_{effluent}$	= organic load to the passing through wastewater treatment and discharged to the receiving water body as effluent, tonne BOD ₅

Equation A3.6–21

EF_{CH_4} Receiving water body = B_0 × MCF	
EF_{CH_4} Receiving water body	= emission factor, kg CH ₄ /kg BOD ₅ for wastewater discharged to receiving water bodies
B_0	= theoretical maximum CH ₄ producing capacity, 0.36 kg CH ₄ /kg BOD ₅ (AECOM 2011).
MCF	= methane correction factor (MCF), fraction. IPCC 2019 Refinement Tier 1 default value of 0.11, for unspecified receiving water body type.

The BOD₅ discharged to receiving water bodies varies by treatment technology. The total BOD₅ discharged to receiving water bodies can be determined as a mass balance based on the removal efficiency of the treatment technology.

Equation A3.6–22

$OrganicLoad_{effluent} = \sum_t [OrganicLoading_t \times Organics_Removed_Via_Treatment_t]$	
$OrganicLoad_{effluent}$	= quantity of organics, measured as BOD ₅ discharged to receiving water bodies from treatment technology of type t, tonne BOD ₅
$OrganicLoad_t$	= organic load to the wastewater treatment/discharge systems of type t, tonne BOD ₅
$BOD\ Removal\ Efficiency_t$	= typical efficiency of wastewater treatment technology, in Canada, at removing BOD ₅ from wastewater (Table A3.6–13)

Emissions from Anaerobic Digestion of Sludge at Wastewater Treatment Facilities

Emissions from anaerobic digestion occurring at wastewater treatment plants are reported under Wastewater, in accordance with the 2019 Refinement to the 2006 IPCC Guidelines (IPCC, 2019). Anaerobic digestion and composting of sludge occurring off-site from the wastewater treatment plants, however, are reported under Biological Treatment (section A3.6.2).

To calculate emissions from anaerobic digestion, the BOD₅ removed as sludge must be converted to a mass of total suspended solids (TSS), and the fraction of volatile suspended solids (VSS) must be determined. The ratio of TSS sludge produced per unit BOD₅ removed from wastewater as sludge (TSS/BOD₅) and the VSS content of the sludge (VSS/TSS ratio) can be estimated based on the treatment technology used. The TSS/BOD₅ and VSS/TSS ratios are approximate and averaged for a given technology (Equation A3.6–23 to Equation A3.6–27). They are not representative of facility-level operations, which can have a wide variety of operating conditions (temperature, solids retention time, etc.). On aggregate, however, these values are believed to provide a reasonable approximation of the mean sludge characteristics from all facilities in a region of a given type.

Equation A3.6–23

$$TSS_{Sludge} = BOD_5 \text{ Removed as Sludge} \times \text{Sludge TSS Per } BOD_5 \text{ Removed}$$

TSS_{Sludge}	=	mass of total suspended solids in sludge removed from wastewater, tonne
$BOD_5 \text{ Removed as Sludge}$	=	BOD_5 removed from wastewater as sludge, tonne BOD_5
$\text{Sludge TSS Per } BOD_5 \text{ Removed}$	=	conversion factor, mass of TSS per unit of wastewater BOD_5 removed as sludge (tonne / tonne BOD_5); a function of treatment technology (Table A3.6–15)

To date, 89 municipal wastewater treatment facilities have been identified as having on-site anaerobic digestion of sludge. The emissions from anaerobic digestion are calculated at the facility level, based on the estimated population served by that facility and the sludge generated based on the treatment technology employed, then aggregated by province. Uncertainty at the facility level is considered high (not yet quantified) because the parameters used represent general technology averages and not facility-specific configurations. Estimates are likely unreliable until they are aggregated to the provincial level.

Sludge transfers between facilities are also accounted for. In some municipalities sludge may be transferred from smaller wastewater treatment facilities to be processed at larger ones.

Equation A3.6–24

$$CH_4 \text{ AD produced} = TSS_{ReductionAD} \times BiogasGen_{Frac} \times FCH_4 \text{ Biogas} \times Density_{Biogas} \times 0.001$$

$CH_4 \text{ AD produced}$	=	methane generated from anaerobic digestion of sludge (tonne)
$TSS_{ReductionAD}$	=	mass of total suspended solids reduced by anaerobic digestion (kg)
$BiogasGen_{Frac}$	=	volume of biogas generated per unit of TSS consumed in anaerobic digestion (m^3/tonne)
$FCH_4 \text{ Biogas}$	=	fraction of biogas this is CH_4 , by mass
$Density_{Biogas}$	=	density of biogas (kg/m^3)
0.001	=	unit conversion kg/m^3 to tonne/ m^3

Anaerobic digestion of sludge consumes the VSS portion of sludge. The reduction in sludge quantity (mass) is based on the volatile suspended solids fraction.

Table A3.6–15 Sludge Characteristics (Conversion from BOD_5 to Total Suspended Solids and Volatile Solids Fraction)

Treatment Category	SludgeTSS / BOD_5 (kg/kg)	VSS/TSS	Source
No Treatment	N/A		
Primary	1.75	0.83	Envirosim (2019)
Aerobic Lagoon	0.17	0.35	Envirosim (2019)
Anaerobic Lagoon	0.55	0.45	Envirosim (2019)
Facultative Lagoon	0.33	0.33	Envirosim (2019)
Other / Unspecified Lagoon	0.33	0.33	Modelling as Facultative Lagoon
Secondary Anaerobic	0.95	0.815	Modelling as Secondary Activated Sludge
Secondary Activated Sludge	0.95	0.815	Envirosim (2019)
Trickling Filter	1.08	0.83	Envirosim (2019)
Trickling Filter – High Rate	1.23	0.84	Envirosim (2019)
Rotating Biological Contactor	1.08	0.83	Modelling as Trickling Filter
Sequencing Batch Reactor	0.95	0.815	Modelling as Secondary Activated Sludge; Mahvi (2008); U.S. EPA (1999)
Secondary Biofiltration	0.95	0.815	
Secondary with Biological Nutrient Removal	0.95	0.815	Envirosim (2019)
Septic	0.25	0.5	ECCC Estimate based on IPCC (2019) and Washington State (2004)
Septic with Marine Outfall	0.25	0.5	ECCC Estimate based on IPCC (2019) and Washington State (2004)
Wetland	N/A		Assuming no sludge removal
Other / Unknown	0.33		Modelling as facultative lagoon
Note: N/A = Not available			

	$TSS_{Reduction_{AD}} = TSS_{Sludge} \times \frac{VSS}{TSS} ratio \times FracVSSRemoval_{AD}$
$TSS_{Reduction_{AD}}$	= mass of total suspended solids reduced by anaerobic digestion (tonne)
TSS_{Sludge}	= mass of total suspended solids in sludge (tonne)
$FracVSS$	= fraction of sludge mass that is volatile suspended solids. $FracVSS$ is a function of the treatment technology from which the sludge originates (Table A3.6–15)
$FracVSSRemoval_{AD}$	= fraction of VSS that is consumed by anaerobic digestion (fraction).

Methane Recovery

Methane recovery for anaerobic digestion of sludge is universally practiced in Canada. Fugitive loss and CH_4 emissions are assumed to be 2.1% of the CH_4 produced, for anaerobic digestion of sludge at wastewater treatment facilities.

Equation A3.6–26 **Fugitive Emissions from Wastewater Anaerobic Digesters**

$$CH_4_{AD\ Emission} = CH_4_{AD\ Produced} \times FugitiveLoss_{percent}/100$$

$CH_4_{AD\ Emission}$	= methane emitted from anaerobic digestion of sludge at wastewater treatment facilities (tonne)
$CH_4_{AD\ Produced}$	= methane produced from anaerobic digestion of sludge (tonne)
$FugitiveLoss_{percent}$	= percentage of biogas (and CH_4) emitted from fugitive loss

Sludge Available for Other Fates (Sludge Accounting)

Secondary to the wastewater treatment emissions, sludge produced and remaining after anaerobic digestion on-site is used to estimate the quantities of sludge landfilled. The sludge remaining after on-site anaerobic digestion is determined as shown in Equation A3.6–27. Because anaerobic digestion only consumes the VSS portion of sludge, the VSS fraction is updated as shown in Equation A3.6–28.

Equation A3.6–27 **Sludge Mass Total Suspended Solids (Dry Weight) Available After On-Site Anaerobic Digestion**

$$TSS_{Available} = TSS_{Sludge} - TSS_{Reduction_{AD}}$$

$TSS_{Available}$	= The mass of sludge total suspended solids (in other words the dry weight of sludge) available after wastewater treatment and on-site anaerobic digestion of sludge (kg TSS or kg Dry Weight Sludge).
TSS_{Sludge}	= mass of total suspended solids in sludge, before anaerobic digestion (kg)
$TSS_{Reduction_{AD}}$	= mass of TSS reduced by anaerobic digestion (kg)

Equation A3.6–28 **Sludge Volatile Suspended Solids Fraction After Anaerobic Digestion**

$$VSS_{Updated} = \frac{TSS_{Sludge} * FracVSS - TSS_{Reduction_{AD}}}{TSS_{Sludge} - TSS_{Reduction_{AD}}}$$

$VSS_{updated}$	= volatile suspended solids fraction of sludge having undergone anaerobic digestion (fraction)
TSS_{Sludge}	= mass of total suspended solids in sludge, before anaerobic digestion (kg)
$FracVSS$	= fraction of sludge mass that is VSS, before anaerobic digestion (fraction)
$TSS_{Reduction_{AD}}$	= mass of TSS reduced by anaerobic digestion (kg)

The VSS fraction of all sludge produced in a province or territory is determined from the weighted average of sludge produced from each treatment technology after accounting for any on-site anaerobic digestion.

Sludge Distribution

Quantities of sludge incinerated and composted are reported directly from the facilities. Sludge sent to these fates are discussed in section A3.6.2 (Biological Treatment of Solid Waste) and A3.6.3 (Incineration). Sludge sent to landfill or land-applied for agriculture or land-restoration must be estimated. Sludge remaining after point source fates (compost and incineration) is distributed to landfill or land-application according to provincial ratios estimated by Cheminfo (Cheminfo, 2018). Estimated fates of wastewater treatment sludge are shown in Figure A3.6–6.

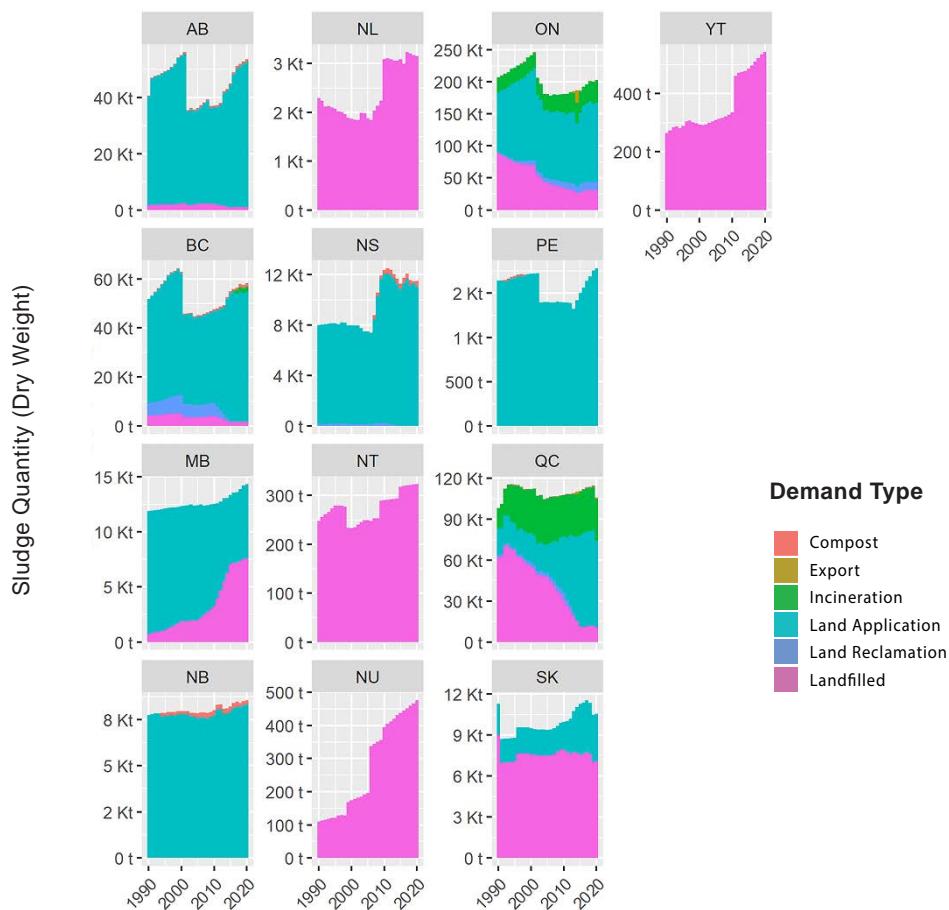
Equation A3.6–29 Calculation of Sludge Distribution to Landfills as Part of Sludge Flow Accounting

$$\text{Sludge Landfilled} = [\text{SS}_{\text{Available}} - \text{SS}_{\text{BioTrtmt}} - \text{SS}_{\text{Incinerated}} - \text{SS}_{\text{Exported}}] \times \text{PropLF}$$

$\text{SS}_{\text{Available}}$	= mass of sewage sludge available from wastewater treatment, after accounting for reductions from on-site anaerobic digestion at the wastewater treatment facilities
$\text{SS}_{\text{BioTrtmt}}$	= mass of sludge sent to biological treatment, which includes composting and anaerobic digestion (the product of which is assumed to not re-enter the pool of sludge potentially destined for landfill)
$\text{SS}_{\text{Incinerated}}$	= mass of sludge incinerated, tonne
$\text{SS}_{\text{Exported}}$	= mass of sludge exported, tonne
Prop_{LF}	= proportion of sewage sludge remaining that is landfilled, as opposed to land-applied on agricultural land, forest or as part of land-reclamation (varies by province and over time), ratio.

Estimated fates of wastewater treatment sludge are shown in Figure A3.6–6.

Figure A3.6–6 Sludge Flow Accounting, Estimated Sludge Fates by Province and Territory



A3.6.4.1.1. N₂O Emissions from Municipal Wastewater Treatment/Discharge

Methodology

Nitrous oxide (N₂O) is associated with the degradation of nitrogen components in wastewater, which are introduced from urea, nitrate and protein in human sewage as well as inputs from other household wastewater, including inputs from shower drains, sink drains, washing machines, etc. (IPCC, 2006). N₂O emissions are estimated from both the N₂O formed during the wastewater treatment process and from N₂O formed in the receiving water body into which wastewater is discharged. Emissions from the treatment process occur from anoxic zones in the treatment process and nitrification, and are most common in treatment processes that have biological nutrient removal stages. Emissions from the receiving water body are a product of nitrogen remaining in the discharged wastewater effluent. Some of this nitrogen is converted to nitrous oxide through natural microbial processes and emitted.

Emissions are largely based on the IPCC 2019 Refinement (IPCC, 2019). For wastewater N₂O emissions, the 2019 Refinement represents a substantial update in comparison with the 2006 Guidelines. Since the 2006 IPCC Guidelines, many more studies have been conducted on treatment emissions nitrous oxide from wastewater treatment. Among other things, the 2019 IPCC Refinement provides the following updates compared to the 2006 IPCC Guidelines:

- New data source for protein consumption
- Updated and new parameters for estimating nitrogen introduced to wastewater
- New parameters to account for nitrogen removed from wastewater treatment
- Updated emission factors for treatment-based emissions
- Additional emission factors for effluent emissions from the receiving water body for water bodies that have pre-existing high nutrient loads

Methodology to determine nitrogen in wastewater

The first step to calculating N₂O in wastewater is to determine the amount of nitrogen entering into the wastewater stream; this is largely a function of population and per capita protein consumption. The nitrogen introduced to wastewater is multiplied by an emission factor specific to each treatment type. The amount of nitrogen introduced into each treatment system is based on the amount of protein consumed, with adjustment to account for non-consumed protein (i.e., garbage disposals), industrial and commercial co-discharge and additional nitrogen from household products (Equation A3.6–30).

Equation A3.6–30 Nitrogen entering the wastewater treatment system

$$N = Pop * Protein Consumed * F_{NPR} * N_{NH} * F_{NON-CON} * F_{IND-COM}$$

<i>N</i>	=	The amount of nitrogen entering the treatment system
<i>Pop</i>	=	The population using the treatment system
<i>F_{NPR}</i>	=	fraction of protein that is nitrogen
<i>F_{NON-CON}</i>	=	factor for N in non-consumed protein
<i>F_{IND-COM}</i>	=	Factor for industrial and commercial co-discharge
<i>N_{NH}</i>	=	additional nitrogen from household products

Protein consumption is derived using the protein availability from the Food and Agricultural Organization statistical database (FAOSTAT, n.d.). Protein availability is converted to protein consumption using the previously published Statistics Canada analysis on nutrients in the food supply, with a ratio of 0.678 (Statistics Canada, 2009), which accounts for the protein available after loss. The combined FAOSTAT data combined with further accounting for protein loss is assumed to be representative of protein consumption. The variables *F_{NPR}* represents the fraction of nitrogen that is protein and a value of 0.16 kg N/kg protein is used (IPCC, 2019). *F_{IND-CON}* and *N_{NH}* are additional parameters to account for additional nitrogen inputs that may enter the wastewater stream, either from industrial and commercial sources as well as from the use of household products. The values for *F_{IND-CON}* and *N_{NH}* are 1.25 and 1.17, respectively (IPCC, 2019).

For the parameter *F_{NON-CON}*, the 2019 Refinement default factor for nitrogen inputs from waste disposed in-sink (garbage disposals) is used. The *F_{NONCON}* for North America is 1.13 where food is disposed in-sink and 1.0 when food is not disposed in-sink. For Canada, 10% of households use in-sink garbage disposal (IPCC, 2019, Table 6.10B). As no regional specific information about where in-sink garbage disposal (garbage disposals) are permitted, it is assumed that the 10% of households using in-sink disposal are evenly distributed across Canada. To determine the total (net) N inputs from food disposed in sink, we can

apply the default F_{NONCON} factor of 1.13 for food disposed in sink to the 10% of the population that does so, and the default F_{Non_Con} of 1.0 for cases where food is not disposed in sink to the remaining 90% of the population, resulting in an overall F_{NONCON} values of 1.013.

Treatment based emissions

Depending on the type of wastewater treatment, N_2O emission factors can vary. Thus since the amount of nitrogen entering in the wastewater stream is population dependent, it is important to estimate which fraction of the population is associated with each treatment type. This derivation of the population using various treatment types is explained in the preceding section in the discussion of CH_4 emissions from wastewater, resulting in the variable $Fraction_{tech}$. Then, N_2O emissions are developed using the following Equation A3.6–31, accounting for each treatment type in Canada. Emission factors are largely based on the IPCC 2019 Refinement, with some adaptation based on Canadian circumstances (Table A3.6–16). The emissions for all treatment types are then totalled to account for national and provincial totals.

Equation A3.6–31 Direct N_2O emissions from wastewater treatment plants

$$N_2O_{Treatment} = N_{wastewater} * Fraction_{tech} * EF_{Tech} * 44/28$$

$N_2O_{Treatment}$	=	The N_2O emissions arising directly from wastewater treatment
$N_{wastewater}$	=	The amount of nitrogen entering the wastewater stream
EF_{Tech}	=	EF_{Tech_T} is the emission factor of kg Nitrogen emitted (kg $N_2O\text{-N}/kg N$)
$Fraction_{tech}$	=	fraction of treatment type used in Canada, by population
44/28	=	the stoichiometric conversion from $N_2O\text{-N}$ to N_2O

Discharge (to receiving waterbody) based emissions

N_2O emissions from municipal wastewater treatment facilities are estimated using the amount of nitrogen discharged to the aquatic environment. The first step for calculating the effluent emissions is to determine the nitrogen remaining in the effluent, as a portion of this nitrogen will be removed during the treatment process (Table A3.6–17). Nitrogen removal can vary between 0% for instances of no treatment, up to 68% when septic tanks and land dispersal fields are used. For the purposes of the inventory, Table 6.10c of the 2019 refinement is used.

After accounting for nitrogen removed at wastewater treatment, the remaining nitrogen introduced to the wastewater stream is multiplied by an emission factor of 0.005 kg $N_2O\text{-N}$ / kg $N_2O\text{-N}$ in wastewater, as shown in Equation A3.6–32.

Table A3.6–16 N_2O emission factors and N removal for different treatment types

Treatment Category	EF (kg $N_2O\text{-N}/kg N$)	N-Removal Fraction	EF Source	N-Removal Source
No Treatment	0	0	IPCC (2019)	IPCC (2019)
Primary	0	0.1	ECCC Estimate	
Aerobic Lagoon	0	0.4		
Anaerobic Lagoon	0	0.4	IPCC (2019)	
Facultative Lagoon	0	0.4	ECCC Estimate	
Other / Unspecified Lagoon	0	0.4	Model as facultative lagoon	
Secondary Anaerobic	0	0.4		
Secondary Activated Sludge	0.016	0.4		
Trickling Filter	0.016	0.4		
Trickling Filter – High Rate	0.016	0.4		
Rotating Biological Contactor	0.016	0.4		
Sequencing Batch Reactor	0.016	0.4		
Secondary Biofiltration	0.016	0.8		ECCC Estimate
Secondary with Biological Nutrient Removal	0.016	0.8		IPCC (2019)
Septic	0.0045	0.68		
Septic with Marine Outfall	0	0.15		
Wetland	0	1		ECCC Estimate
Other / Unknown	0.016	0.4	Model as facultative lagoon	Model as facultative lagoon

$$N_2O = EF_{N2O-N} \times N_{wastewater} \times 44/28$$

N_2O	=	N_2O emissions in the inventory year, kg N_2O /year
EF_{N2O-N}	=	emission factor for N_2O emissions from discharged wastewater, kg N_2O -N/kg N.
$N_{wastewater}$	=	nitrogen in wastewater, kg N/yr
$44/28$	=	stoichiometric factor to convert nitrogen to N_2O

Nitrogen removed from sludge is not estimated because of a lack of data on nitrogen concentration in sewage sludge. The 2006 IPCC Guidelines default value of 0 is used.

A3.6.4.1.2. **CO₂ Emissions from Municipal Wastewater Treatment/Discharge**

CO₂ emissions from wastewater are of biogenic origin. According to the 2006 IPCC Guidelines, CO₂ from the combustion or decay of short-lived biogenic material removed from where it was grown is reported as zero in the Waste sector. Therefore, these emissions are not considered for wastewater treatment.

Table A3.6–17 Canadian Protein Supply and Consumption

Year	Protein Supply (FAOSTAT, g/capita/day)	Protein Consumption (g/capita/day)
1990	96.1	67.2
1991	96.2	67.3
1992	95.9	67.2
1993	95.8	67.1
1994	99.6	69.7
1995	98.0	68.6
1996	98.7	69.1
1997	100.5	70.4
1998	103.3	72.3
1999	107.1	75.0
2000	106.1	74.2
2001	105.1	73.5
2002	105.3	73.7
2003	104.0	72.8
2004	104.8	73.4
2005	102.1	71.5
2006	103.5	72.5
2007	104.4	73.1
2008	104.7	73.3
2009	103.1	72.2
2010	104.1	72.9
2011	103.9	72.7
2012	104.6	73.2
2013	105.0	73.5
2014	98.7	69.1
2015	97.6	68.3
2016	102.4	71.7
2017	104.7	73.3
2018	104.1	72.9
2019	N/A	72.9
2020	N/A	72.9

Note:
N/A = Not available

A3.6.4.2. Industrial Wastewater Treatment – CO₂, CH₄ and N₂O

Estimates for CO₂, CH₄ and N₂O emissions from industrial facilities with on-site wastewater treatment are handled facility by facility following a Tier 3 approach (IPCC, 2006), making use of the GHGRP, the National Pollutant Reporting Program (NPRI) and some historical facility survey data. Industrial on-site wastewater treatment systems can receive varying organics loads, depending on industry type, facility size and production levels. Methane recovery varies facility by facility.

A3.6.4.2.1. Data Sources and Methodology

A Tier 3 approach based on information directly collected from individual facilities was deemed more accurate than the default approach. The primary data source is the GHGRP which requires any facility emitting >10,000 tonnes of CO₂ eq to report their emissions to ECCC. Facilities are required to report CH₄, N₂O and any non-biogenic CO₂ emissions from wastewater sources separately from other GHG sources; this data is used directly in the NIR. Previously, ECCC conducted a voluntary industrial wastewater survey. While the survey was discontinued, previous information collected was used to supplement the GHGRP data. The historical survey only covered CH₄. In addition, the historical survey is used for determining CH₄ recovery, which is not currently available for wastewater in the GHGRP data.

It is believed the N₂O emissions reported to the GHGRP are facility/treatment based, while nitrogen in industrial effluents are not reported as part of this program. Therefore, to account for N₂O that may be a result of nitrogen discharged to waterbodies, the NPRI discharges to water was used as a data source. To make use of this data source, reported N-effluent data from the NPRI are used to calculate N₂O emissions with Equation A3.6–32, using the same emission factor as for domestic wastewater effluents. Finally, to address time series consistency emissions data sources are extrapolated back to 1990. This is necessary because the GHGRP and NPRI programs started in 2004 and 2011, respectively. Where emissions are covered by historical survey data, no extrapolation is done, rather the survey data is used. Extrapolation is done by industry category (defined by NAICS codes): earliest and latest values are held constant through time. Data gaps, if they exist, are completed using linear interpolation. CH₄ recovery from the historical survey is extrapolated forward to the reporting year in the same way.

ANNEX 4

COMPARISON OF SECTORAL AND REFERENCE APPROACHES, AND THE NATIONAL ENERGY BALANCE

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This annex covers the energy and the CO₂ emission results from the reference approach (RA), a comparison of the results from the RA with those estimated by the sectoral approach (SA), and a summary of the national energy balance, which is the main energy data source for both the RA and the SA. Section A4.4 contains a general discussion on the merits of using implied emission factors.

A4.1. Comparison of Reference Approach with Sectoral Approach

A comparison of results from the RA and the SA serve as a check of energy available versus that consumed by all sectors, and the corresponding CO₂ emissions from fossil fuel combustion. Checks of RA and SA results for all years from 1990 to 2020 are an integral part of reporting to the United Nations Framework Convention on Climate Change (UNFCCC).

Direct comparison of energy consumption in the RA and SA shows significant discrepancies, since the SA total does not include some of the non-energy use of fossil fuels and feedstocks. Comparison of the RA and SA shows an 11.9% or larger variation in energy. Excluding the non-combustion energy of certain feedstocks and fossil fuels ensures that the RA and the SA are comparing similar sources. When the RA energy amounts include adjustments for non-energy use of fossil fuels and feedstocks, the difference between the SA and adjusted RA varies from -2.25 to 0.35%. Table A4–1 shows a comparison of the original and adjusted RA and SA.

No adjustments were necessary for the emissions estimate in the RA since online CRF Reporting software, supplied by the UNFCCC, correctly removes emissions associated with non-energy and feedstock use and allocates them to industrial processes and product use sectors. Comparison of the RA and SA emission estimates, as seen in Table A4–1, shows an overall -1.51% to 1.10% variation.

A4.2. Reference Approach Methodology

The RA follows the 2006 Intergovernmental Panel on Climate Change (IPCC) Guideline's designated method with the use of country-specific fuel energy contents (in higher heating value [HHV]/gross calorific value [GCV]) and emission factors. Canada and the United States use HHVs to report the energy content of fuels. Fuel supply and demand reported by industries to the various surveys that feed into the compilation of the *Report on Energy Supply and Demand in Canada* (RESID) (Statistics Canada, 1990–) are in physical units. Chapter 3, section 3.2.2 International Bunker Fuels, and annex sections A3.2.2.1 Civil Aviation, and A3.2.2.2 Navigation present fuel allocation for International bunkers.

For primary fuels (crude oil, ethane, natural gas liquids, coal and natural gas), the stock change data have been adjusted to account for inter-product transfers, stock variation and other adjustments, all of which are reported separately in the RESID and all of which directly impact fuel availability. Apparent consumption is determined using this adjusted stock change number. Similarly, the stock change data for secondary fuels takes into consideration inter-product transfers, international bunkers, stock variation and other adjustments.

Table A4-1 Comparison of Adjusted Reference Approach and Sectoral Approach for Canada

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Overall Energy Comparison																
Reference Approach (PJ)	7 102	6 978	7 173	7 232	7 461	7 635	7 999	8 226	8 258	8 688	8 851	8 737	8 873	9 183	9 187	8 996
Sectoral Approach (PJ)	6 322	6 174	6 403	6 440	6 654	6 824	7 047	7 198	7 256	7 556	7 923	7 801	7 900	8 127	8 051	8 028
Percent Difference without Adjustment (%)	12.3	13.0	12.0	12.3	12.1	11.9	13.5	14.3	13.8	15.0	11.7	12.0	12.3	13.0	14.1	12.1
Reference Approach with Non-Energy Use of Fossil Fuels and Feedstock Adjustment (PJ)	6 279	6 151	6 324	6 348	6 558	6 727	6 936	7 110	7 160	7 509	7 765	7 625	7 732	7 995	7 915	7 847
Percent Difference with Adjustment—100% x (RA-SA)/SA	-0.69	-0.37	-1.23	-1.44	-1.44	-1.43	-1.58	-1.23	-1.32	-0.63	-1.99	-2.25	-2.13	-1.62	-1.68	-2.25
Adjusted Non-Energy Fossil Fuels and Feedstocks																
Non-Energy Use of Gaseous Fuels (PJ)	178	180	176	207	230	209	240	260	258	260	236	205	165	171	183	170
Non-Energy Use of Liquid Fuels (PJ)	542	532	558	565	569	590	714	750	730	807	735	800	870	909	977	877
Non-Energy Use of Solid Fuels (PJ)	103	116	115	113	105	110	108	107	110	112	115	107	106	107	111	102
Overall Emission Comparison																
Reference Approach (Gg CO ₂)	413 915	404 156	413 724	412 709	425 607	434 983	446 126	460 581	466 263	485 356	502 501	494 676	500 855	519 095	512 001	509 175
Sectoral Approach (Gg CO ₂)	411 251	401 787	414 842	413 514	425 770	436 991	450 497	463 732	469 468	484 725	507 706	501 712	505 164	520 729	516 812	515 292
Percentage Difference (%)	0.65	0.59	-0.27	-0.19	-0.04	-0.46	-0.97	-0.68	-0.68	0.13	-1.03	-1.40	-0.85	-0.31	-0.93	-1.19
Liquid Fuels																
Reference Approach (Gg CO ₂)	204 389	191 899	192 012	194 474	200 062	201 343	204 205	212 409	216 723	220 317	223 792	223 435	226 420	243 065	247 092	245 146
Sectoral Approach (Gg CO ₂)	203 146	190 901	194 008	195 791	200 795	203 411	208 249	215 849	219 441	221 492	224 071	227 450	226 862	240 889	248 914	245 299
Percentage Difference (%)	0.61	0.52	-1.03	-0.67	-0.37	-1.02	-1.94	-1.59	-1.24	-0.53	-0.12	-1.77	-0.19	0.90	-0.73	-0.06
Solid Fuels																
Reference Approach (Gg CO ₂)	87 307	90 621	92 759	84 378	88 517	89 620	92 263	99 920	104 726	105 155	114 279	113 671	110 121	108 307	101 156	102 790
Sectoral Approach (Gg CO ₂)	87 009	90 261	92 689	84 924	89 346	90 769	92 754	99 911	105 744	105 923	115 548	113 826	111 514	110 523	102 787	104 219
Percentage Difference (%)	0.34	0.40	0.07	-0.64	-0.93	-1.27	-0.53	0.01	-0.96	-0.73	-1.10	-0.14	-1.25	-2.01	-1.59	-1.37
Gaseous Fuels																
Reference Approach (Gg CO ₂)	121 772	121 254	128 472	133 327	136 370	143 432	149 058	147 807	144 294	159 355	163 873	157 028	163 632	167 092	163 079	160 683
Sectoral Approach (Gg CO ₂)	120 648	120 243	127 662	132 268	134 970	142 222	148 891	147 523	143 760	156 778	167 527	159 892	166 104	168 684	164 435	165 215
Percentage Difference (%)	0.93	0.84	0.63	0.80	1.04	0.85	0.11	0.19	0.37	1.64	-2.18	-1.79	-1.49	-0.94	-0.83	-2.74

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Overall Energy Comparison															
Reference Approach (PJ)	9 021	9 422	9 220	8 909	9 110	9 319	9 430	9 415	9 325	9 656	9 468	9 553	9 819	9 920	9 138
Sectoral Approach (PJ)	7 917	8 346	8 144	7 797	7 940	8 171	8 149	8 267	8 309	8 401	8 210	8 416	8 736	8 741	8 040
Percent Difference without Adjustment (%)	13.9	12.9	13.2	14.3	14.7	14.0	15.7	13.9	12.2	14.9	15.3	13.5	12.4	13.5	13.7
Reference Approach with Non-Energy Use of Fossil Fuels and Feedstock Adjustment (PJ)	7 794	8 202	8 088	7 824	7 892	8 026	8 067	8 156	8 135	8 398	8 168	8 368	8 623	8 716	8 016
Percent Difference with Adjustment—100% x (RA-SA)/SA	-1.56	-1.73	-0.69	0.35	-0.60	-1.78	-1.01	-1.34	-2.10	-0.03	-0.52	-0.57	-1.29	-0.29	-0.31
Adjusted Non-Energy Fossil Fuels and Feedstocks															
Non-Energy Use of Gaseous Fuels (PJ)	156	155	126	138	138	158	161	147	134	148	149	152	147	147	150
Non-Energy Use of Liquid Fuels (PJ)	959	955	905	869	994	1 029	1 102	1 025	964	1 036	1 069	947	961	978	906
Non-Energy Use of Solid Fuels (PJ)	112	110	101	77	86	106	100	88	92	75	83	85	88	79	67
Overall Emission Comparison															
Reference Approach (Gg CO ₂)	502 004	527 120	516 440	495 425	499 270	499 563	501 575	505 819	502 540	520 781	505 440	515 949	525 538	527 259	478 867
Sectoral Approach (Gg CO ₂)	506 412	532 151	517 424	491 304	500 054	507 236	503 558	509 750	509 486	515 134	502 448	514 508	526 286	526 693	479 261
Percentage Difference (%)	-0.87	-0.95	-0.19	0.84	-0.16	-1.51	-0.39	-0.77	-1.36	1.10	0.60	0.28	-0.14	0.11	-0.08
Liquid Fuels															
Reference Approach (Gg CO ₂)	238 977	247 571	240 321	242 471	239 820	232 920	241 369	235 252	229 676	242 769	242 595	245 604	251 476	251 181	222 056
Sectoral Approach (Gg CO ₂)	242 191	248 927	240 603	236 885	241 080	241 931	241 109	241 859	237 789	239 676	237 743	243 039	249 997	252 280	222 355
Percentage Difference (%)	-1.33	-0.54	-0.12	2.36	-0.52	-3.72	0.11	-2.73	-3.41	1.29	2.04	1.06	0.59	-0.44	-0.13
Solid Fuels															
Reference Approach (Gg CO ₂)	99 277	104 593	99 282	81 101	84 714	74 736	68 314	69 732	64 142	67 901	61 712	62 090	49 224	48 543	40 523
Sectoral Approach (Gg CO ₂)	100 545	105 628	99 784	83 472	84 892	74 860	69 447	68 848	65 675	67 514	61 990	62 059	49 618	47 837	38 767
Percentage Difference (%)	-1.26	-0.98	-0.50	-2.84	-0.21	-0.16	-1.63	1.29	-2.33	0.57	-0.45	0.05	-0.79	1.48	4.53
Gaseous Fuels															
Reference Approach (Gg CO ₂)	163 190	174 301	176 182	171 282	174 167	191 340	191 206	200 204	208 164	209 463	200 503	207 647	224 228	226 923	215 621
Sectoral Approach (Gg CO ₂)	163 113	176 939	176 380	170 375	173 512	189 876	192 314	198 410	205 463	207 295	202 085	208 803	226 062	225 965	217 473
Percentage Difference (%)	0.05	-1.49	-0.11	0.53	0.38	0.77	-0.58	0.90	1.31	1.05	-0.78	-0.55	-0.81	0.42	-0.85

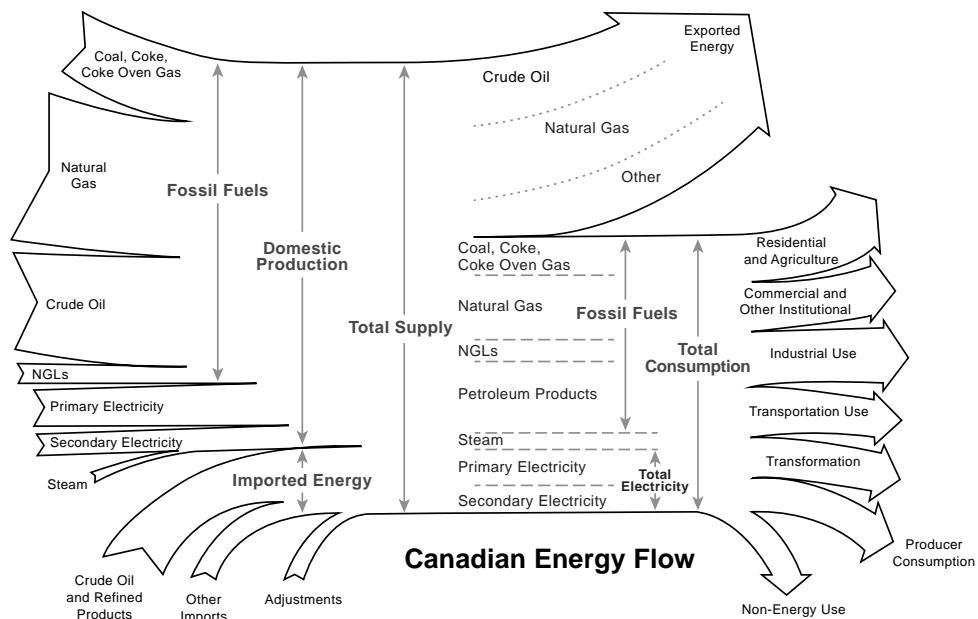
Once the apparent consumption is determined, country-specific fuel energy contents and carbon emission factors allow for the calculation of carbon content and emissions. Energy content values come from the following sources: RESD (Statistics Canada, 1990–), the 1998 *Fossil Fuel and Derivative Factors* (McCann, 2000) and Measurement Canada, an Industry Canada agency. For the majority of fossil fuels, the applied emission factors and oxidation factors are from McCann (2000), and the 2006 IPCC Guidelines.

Table A4–2 presents the applied emission factors, energy contents and oxidation values in the RA. The RESD supplies the energy content values, with the exceptions of bituminous coal, lignite, crude oil, heavy fuel oil, LPGs, natural gas, NGLs, petroleum coke and still gas, where weighted factors, calculated yearly, account for the quantity and variation of energy content at the point of consumption, such as commercial usage or self-generated usage. For example, in provinces with natural gas production, there are two emission factors for natural gas: marketable natural gas, sold to consumers, and non-marketable natural gas, combusted by the producers of natural gas. The composition of non-marketable natural gas includes more complex hydrocarbons unlike marketable natural gas which, typically, contains over 95% CH₄.

A4.3. National Energy Balance

This section provides a general background on the national energy balance and its data quality framework. In Canada, the Energy and Environment Statistics Division (EESD) of Statistics Canada is responsible for the collection, compilation and dissemination of energy data under the authority of the *Statistics Act*.¹ The RESD is the primary source of activity data used to estimate GHG emissions for the Energy sector and is available on Statistics Canada's website.² Emission estimates for the Industrial Processes and Product Use sector also use the non-energy and feedstock information from the RESD as a source of activity data. The RESD is an accounting of energy forms in Canada from import and export activities through to production, stock change and domestic consumption (refer to Figure A4–1 for a sample of an energy flow diagram). It consists of information on crude oil, natural gas, coal, refined petroleum product (RPPs), electricity, steam, non-energy use of fossil fuels, feedstock and other secondary energy forms for all Canadian industrial sectors and other energy use, such as the transportation, residential and commercial sectors.

Figure A4–1 Sample of an Energy Balance Flow Diagram for Canada (RESD)



1 Statistics Canada. *Statistics Act*. <http://laws-lois.justice.gc.ca/eng/acts/S-19>.

2 Statistics Canada. *Report on Energy Supply and Demand in Canada* (Annual). Catalogue No. 57-003-X <http://www.statcan.gc.ca/pub/57-003-x/2017002/tablesectlist-listtableauxsect-eng.htm>.

Table A4–2 Reference Approach Energy Contents and Emission Factors for Canada

Fuel Types			Energy Content, GCV			Carbon Emission Factor – 2020 Value (t C/TJ GCV)	Reference	Oxidation Factors	Comments
			2020 Value	Unit	Reference				
Liquid	Primary Fuels	Crude Oil	39.60	TJ/ML	See Comments	18.79	Refer to Comments	1.0	Weighted energy content and emission factor are based on country-specific data.
		Ethane	17.22	TJ/ML	4	15.46	2	1.0	Total available ethane is consumed as a feedstock in industrial processes.
		Orimulsion	NA	–	–	NA	–	1.0	
		Natural Gas Liquids	25.34	TJ/ML	–	16.33	–	1.0	Propane and butane from natural gas liquids.
	Secondary Fuels	Bitumen	44.46	TJ/ML	4	21.11	3	1.0	Use of asphalt.
		Gas/Diesel Oil	38.35	TJ/ML	4	19.07	2	1.0	Use of diesel fuel oil.
		Gasoline	33.45	TJ/ML	4	18.81	2	1.0	
		Jet Kerosene	37.4	TJ/ML	4	18.67	2	1.0	Use of aviation turbo fuel.
		Liquefied Petroleum Gases (LPG)	27.13	TJ/ML	4	16.59	2	1.0	Country-specific weighted factors for propane and butane from petroleum refineries.
		Lubricants	39.16	TJ/ML	4	19.66	3	1.0	
		Naphtha	35.17	TJ/ML	4	19.33	3	1.0	
		Other Kerosene	37.68	TJ/ML	4	18.53	2	1.0	
		Other Oil	38.8	TJ/ML	4	19.15	2	1.0	Use of light fuel oil.
		Petroleum Coke	44.89	TJ/ML	4	22.62	4	1.0	Country-specific weighted emission factors based on available emission factors for refining and upgrading (of oil sands to synthetic crude oil).
Other Liquid Fuels	Refinery Feedstocks	35.17	TJ/ML	4	19.33	3	1.0	Use of petrochemical feedstock in industrial processes	
	Residual Fuel Oil	42.5	TJ/ML	4	20.27	2	1.0	Use of heavy fuel oil.	
	Shale Oil	NA	–	–	NA	–	–		
	Still Gas	41.18	TJ/ML	4	13.17	4	1.0	Country-specific weighted emission factor based on factors from refinery and from upgrading (of crude from oil sands to synthetic crude oil) activities.	
Other Solid Fuels	Aviation Gasoline	33.52	TJ/ML	4	19.24	3	1.0		
	Other Product Feedstocks	39.82	TJ/ML	4	19.84	3	1.0		
Solid	Primary Fuels	Anthracite	27.7	TJ/kt	4	23.45	3	0.988	
		Other Bituminous Coal	28.37	TJ/kt	4	21.98	6	0.995	Use of Canadian bituminous coal
		Sub-bituminous Coal	18.48	TJ/kt	4	25.97	6	0.994	
		Lignite	16.29	TJ/kt	4	22.50	5, 6	0.996	
		Oil Shale	NA	–	–	NA	–	–	
		Peat	NA	–	–	NA	–	–	
	Secondary Fuels	Coke	28.83	TJ/kt	4	30.02	2	1.0	Previously reported as Coking Coal.
		BKB & Patent Fuel	NA	–	–	NA	–	–	
		Coke Oven Gas	19.14	TJ/GL	4	12.52	2	–	
	Other Solid Fuels	Foreign Bituminous Coal	29.82	TJ/kt	4	23.51	5, 6	0.989	
Gaseous	Primary Fuels	Natural Gas	38.64	TJ/GL	4	13.80	2	1.0	Country-specific weighted emission factor based on proportion of marketable and non-marketable natural gas.
Biomass	Biomass	Municipal Solid Waste	–	–	1	23.94	1	1.0	1) Consists of biomass combustion, for energy purposes, at landfills.
		Solid Biomass	17.87	TJ/kt	4	24.81	7	1.0	1) Consists of industrial and residential biomass consumption.
		Liquid Biomass	16.34	TJ/kt	4	18.82	3, 8	1.0	1) Consists of spent pulping liquor, ethanol and biodiesel.
		Gas Biomass	36.35	TJ/GI	1	13.54	1	1.0	1) Consists of methane from landfill gas.

Notes:

References: (1) IPCC (2006); (2) McCann (2000); (3) Jaques (1992); (4) Statistics Canada (n.d.), #57-003 (2015 data); (5) ECCC (2016); (6) ECCC (2019); (7) US EPA (2003); (8) ICFPA/NCASI (2019).

NA = Not applicable; BKB = Charcoal briquettes; NGL = natural gas liquids; LPG = liquified petroleum gas.

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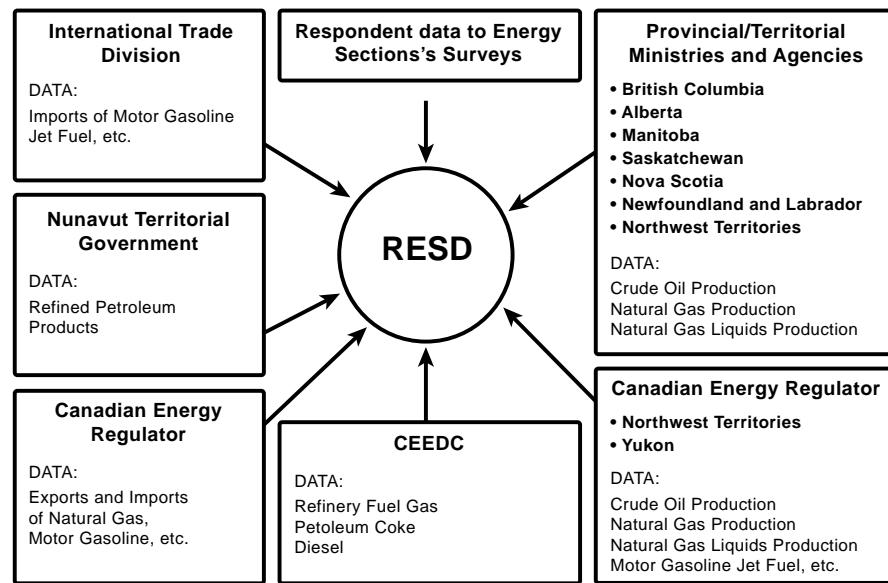
Energy and fossil fuel data are collected using a mix of annual and monthly surveys, along with census data from industry, federal agencies (such as the Canadian Energy Regulator [CER]), provincial energy departments and agencies (such as the Alberta Energy Regulator [AER] and the Alberta Utilities Commissions [AUC]), and the Canadian Energy and Emissions Data Centre (CEEDC). Refer to Figure A4–2, RESD Data Input, for a sample of the energy and fossil fuel data input. The oil and gas information provided by the AER is considered accurate, since it is tied to, oil and gas exploitation permits and federal and provincial royalty schemes.

Various federal departments use the RESD for energy efficiency programs, policy development, energy and emission forecasting, and reporting to the UNFCCC. As such, EESD's quality management system for the RESD includes an internal and external stakeholder review process. Documentation of the quality assurance framework and methodological reports are contained in Statistics Canada's Integrated Meta Database.³ EESD has also established partnerships with various federal government departments, provincial energy ministries, industrial associations and centres of excellence to assist with their quality assurance process.

The following quality criteria are essential to the development of the RESD as set out by Statistics Canada: relevance, accuracy and reliability, timeliness and punctuality, accessibility and clarity, coherence and comparability, and interpretability and metadata.

There are also other internal data quality checks of the information collected through provincial energy departments and various supply, disposition and consumption surveys. For example, the quantities of crude oil reported by the producer are compared to reported receipts from pipeline companies, and the volume data reported by pipelines is verified against refinery receipts. EESD also applies both a top-down approach through the supply and disposition surveys and a bottom-up approach through the Industrial Consumption of Energy (ICE) survey to verify the quality of the data for manufacturing industries. The ICE survey collects fuel consumption data directly from manufacturing industries following the North American Industry Classification System. In addition, an annual Survey of Secondary Distributors of Refined Petroleum Products (SSDRPP) collects data on sale volumes for use in reallocating volumes of heavy fuel oil, light fuel oil, diesel, biodiesel blended diesel fuel, and ethanol blended gasoline to the appropriate consuming sectors. The SSDRPP survey was necessary due to the deregulation of allowable sales of these products from only primary producers (refineries) to include secondary resellers/distributors. Prior to this improvement, fuel volumes reported in the commercial sector incorrectly included all sales by refineries to secondary distributors. The deregulation of the sale of these four fuels started around the year 2000. A consistent approach was applied to the historical dataset to address the misallocated fuel volumes between 2000 and 2008 since the SSD only started collecting sale volumes from 2009 onward.

Figure A4–2 Fossil Fuel and Energy Data Input into the RESD



3 Statistics Canada. Quality Assurance Framework. <http://www.statcan.gc.ca/pub/12-539-x/manage-gestion/4058322-eng.htm>.

Also, as part of EESD's quality framework, an annual "work-in-progress" review has been established with Environment and Climate Change Canada and Natural Resources Canada to review the ICE estimates and the RESD prior to their official release. Industrial stakeholders also participate in the review of ICE data through the Canadian Industry Program for Energy Conservation group. CEDDC also participates in the review of refinery data and the industrial energy statistics.

A4.4. CRF Implied Emission Factors

UNFCCC expert reviewers use the CRF reporting software generated implied emission factors (IEFs) as an initial check for possible outliers. There is merit in the use of IEF checks, especially for a direct comparison of the same commercial fuel between countries, since each of these fuels meets standardized specifications for quality and composition, with an accepted range of carbon content and heating value. Commercial fuels like motor gasoline, diesel and light fuel oil have similar specifications globally, resulting in IEFs that differ by only a few percentage points. However, the percentage difference for fuels like non-marketable (raw) natural gas, crude oil or coal (i.e. bituminous, sub-bituminous, etc.) can vary greatly due to differences in local geology, deposits or fuel categorizations (the latter being especially true in the case of coal).

These checks for IEF outliers are less reliable when fuels are grouped as solid, liquid, gaseous and biomass in CRF Tables 1A1 to Table 1A4. For countries consuming both commercial and non-commercial fuels, and particularly for energy producing nations where non-commercial/non-marketable fuels are readily available and consumed in significant quantities, IEF checks can result in more outliers for certain sectors and fuel groupings (i.e. gaseous and liquid fuels). Generally, countries with large primary energy production (crude oil, synthetic oil, natural gas, etc.) will consume a greater proportion of non-commercial fuels compared to countries with little or no primary energy production and who mostly consume commercial fuels. For these situations, recognizing the impact on IEFs of national circumstances by either increasing its range or conducting IEF checks on a fuel by fuel basis would provide more relevant quality checks.

In Canada's case, shifting the focus of IEF checks from groups of fuels to individual fuels allows a better understanding of their influence on the generation of outliers.

- It allows for an appreciation of the relative proportion of commercial and non-commercial fuel consumed within each fuel grouping.
- It demonstrates how the mix of commercial and non-commercial fuels with wide ranging carbon and energy densities affects the IEF for each fuel.

For example, Canada's implied emission factors can be relatively high for liquid fuels due to the combustion of significant quantities of crude oil, petroleum coke and still gas. In the case of gaseous fuels IEFs can also be high, a result of certain energy producers consuming large quantities of non-marketable natural gas.

Information presented in Table A4–2, illustrates the range of carbon content between each group of fuels, and where even within the group of commercial secondary liquid fuels, the carbon content ranges from 14.74 to 22.23 t C/TJ. For CRF categories consuming a greater portion of still gas or petroleum coke (refinery and upgrader fuels) relative to commercial grade refined petroleum products, the overall IEF for liquid fuels will appear to be an outlier since it will be higher than international averages.

As Canada is a country producing large quantities of fossil fuels, the following categories will most likely generate IEF outliers; 1A1b Petroleum Refining, 1A1ci Manufacture of Solid Fuels, and 1A1cii Oil and Gas Extraction. As mentioned, IEF category checks should be on a fuel by fuel basis or by assessing Parties that have a similar industry makeup; this would generate more comparable results and analysis.

ANNEX 5

ASSESSMENT OF COMPLETENESS

Overall, this inventory report serves as a comprehensive assessment of anthropogenic greenhouse gas (GHG) emissions and removals in Canada. However, emissions for some categories are not estimated (NE) or have been included elsewhere (IE) with other categories for reasons explained in Table A5–1 and Table A5–2. These tables are consistent with Table 9 (Completeness – Information on Notation Keys), for the latest year of the Common Reporting Format (CRF) tables available online here: <https://unfccc.int/ghg-inventories-annex-i-parties/2022>.

Table A5–1 Summary of GHG Sources and Sinks Not Estimated

GHG	Sector	Source/Sink Category	Explanation
C ₁₀ F ₁₈	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
C ₂ F ₆	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
C ₃ F ₈	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
C ₄ F ₁₀	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
C ₅ F ₁₂	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
C ₆ F ₁₄	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
CF ₄	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
CH ₄	Agriculture	3.1 Livestock / 3.A Enteric Fermentation / 3.A.4 Other livestock / Other (please specify) / Fur-bearing Animals	No default emission factors available for Fox and Mink.
CH ₄	Agriculture	3.1 Livestock / 3.A Enteric Fermentation / 3.A.4 Other livestock / Other (please specify) / Rabbit	No default emission factors available for Rabbit.
CH ₄	Agriculture	3.1 Livestock / 3.A Enteric Fermentation / 3.A.4 Other livestock / Poultry	No default emission factor available for Poultry.
CH ₄	Agriculture	3.D Agricultural Soils	Methane emissions from agricultural soils are not estimated because no methodology is available in the 2006 IPCC Guidelines.
CH ₄	Energy	1.B Fugitive Emissions from Fuels / 1.B.1 Solid Fuels / 1.B.1.b Solid Fuel Transformation	The emissions from briquette manufacturing, as a source, has less than 0.05% of total emissions and does not exceed 500 kt CO ₂ eq.
CH ₄	Industrial Processes and Product Use	2.B Chemical Industry / 2.B.1 Ammonia Production	CH ₄ emissions for Ammonia Production are not significant. No default emission factors available for CH ₄ . Country-specific information currently unavailable. There is no methodology provided based on 2006 IPCC Guidelines, Volume 3, Chapter 3.
CH ₄	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Asphalt roofing	CH ₄ emissions are not estimated because no IPCC methodological guidance is provided.
CH ₄	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Other (please specify) / Other and Undifferentiated	CH ₄ emissions are not estimated because no IPCC methodological guidance is provided.
CH ₄	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Road paving with asphalt	CH ₄ emissions are not estimated because no IPCC methodological guidance is provided.

Table A5-1 Summary of GHG Sources and Sinks Not Estimated (cont'd)

GHG	Sector	Source/Sink Category	Explanation
CH ₄	LULUCF	4.B Cropland / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Total Mineral Soils / Rewetted Mineral Soils	Country-specific activity data is currently unavailable to estimate this source category. Efforts are underway to develop improved LULUCF AD, which could potentially aid in these estimates.
CH ₄	LULUCF	4.B Cropland / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Total Organic Soils / Drained Organic Soils	There is no guidance in 2006 IPCC guidelines to report CH ₄ emissions from drained organic soils in Cropland.
CH ₄	LULUCF	4.B Cropland / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Total Organic Soils / Rewetted Organic Soils	Country-specific activity data is currently unavailable to estimate this source category. Efforts are underway to develop improved LULUCF AD, which could potentially aid in these estimates.
CH ₄	LULUCF	4.D Wetlands / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Other Wetlands (please specify)	Currently there are no estimates reported under Other wetlands.
CH ₄	LULUCF	4.E Settlements / 4.E.1 Settlements Remaining Settlements	Currently neither country-specific activity data is available nor methodology exists to estimate this source category.
CH ₄	Waste	5.C Incineration and Open Burning of Waste / 5.C.2 Open Burning of Waste / 5.C.2.1 Biogenic / 5.C.2.1.a Municipal Solid Waste	Open burning at landfills is banned by regulation in provinces and territories. There is anecdotal evidence that open burning does occur in residential settings amounts in mostly rural areas of the country. However, there is currently no up-to-date methodology to estimate these emissions. It is expected that this is not a large source of emissions relative to other activities in Canada.
CH ₄	Waste	5.C Incineration and Open Burning of Waste / 5.C.2 Open Burning of Waste / 5.C.2.2 Non-biogenic / 5.C.2.2.a Municipal Solid Waste	Open burning at landfills is banned by regulation in provinces and territories. There is anecdotal evidence that open burning does occur in residential settings amounts in mostly rural areas of the country. However, there is currently no up-to-date methodology to estimate these emissions. It is expected that this is not a large source of emissions relative to other activities in Canada.
CH ₄	Waste	5.D Wastewater Treatment and Discharge / 5.D.1 Domestic Wastewater	Not available at this time.
CO ₂	Energy	1.B Fugitive Emissions from Fuels / 1.B.1 Solid Fuels / 1.B.1.b Solid Fuel Transformation	The emissions from briquette manufacturing, as a source, has less than 0.05% of total emissions and does not exceed 500 kt CO ₂ eq.
CO ₂	Industrial Processes and Product Use	2.A Mineral Industry / 2.A.4 Other Process Uses of Carbonates / 2.A.4.a Ceramics	Assessments of CO ₂ emissions for 2.A.4.a Ceramics for 2005–2007 and 2011–2020 showed that CO ₂ emissions were below 0.05% of Canada's national total GHG emissions, and did not exceed 500 kt CO ₂ . Assessment for 2005–2007 was performed using Tier 1 methodology from the 2006 IPCC Guidelines, Volume 3, Chapter 2, information from the Canadian Minerals Yearbook, a default carbon content, and default emission factors for both limestone and dolomite calcination. For 2011–2020, industrial process emission estimates were obtained via Canada's Greenhouse Gas Reporting Program.
CO ₂	Industrial Processes and Product Use	2.B Chemical Industry / 2.B.6 Titanium Dioxide Production	CO ₂ emissions for titanium dioxide production are not significant.
CO ₂	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Asphalt roofing	Country specific information is currently unavaialble.
CO ₂	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Other (please specify) / Other and Undifferentiated	Only aggregated CO ₂ emissions are included.
CO ₂	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Road paving with asphalt	Country specific information is currently unavaialble.
CO ₂	LULUCF	4.B Cropland / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Total Mineral Soils / Rewetted Mineral Soils	Country-specific activity data is currently unavailable to estimate this source category. Efforts are underway to develop improved LULUCF AD, which could potentially aid in these estimates.
CO ₂	LULUCF	4.B Cropland / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Total Organic Soils / Rewetted Organic Soils	Country-specific activity data is currently unavailable to estimate this source category. Efforts are underway to develop improved LULUCF AD, which could potentially aid in these estimates.
CO ₂	LULUCF	4.D Wetlands / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Other Wetlands (please specify)	Currently there are no estimates reported under Other wetlands.

Table A5-1 Summary of GHG Sources and Sinks Not Estimated (cont'd)

GHG	Sector	Source/Sink Category	Explanation
CO ₂	LULUCF	4.G Harvested Wood Products / Approach B / Information Item / HWP in SWDS	Country-specific information on wood and paper waste in solid waste disposal sites is currently unavailable.
CO ₂	Waste	5.C Incineration and Open Burning of Waste / 5.C.2 Open Burning of Waste / 5.C.2.1 Biogenic / 5.C.2.1.a Municipal Solid Waste	Open burning at landfills is banned by regulation in provinces and territories. There is anecdotal evidence that open burning does occur in residential settings amounts in mostly rural areas of the country. However, there is currently no up-to-date methodology to estimate these emissions. It is expected that this is not a large source of emissions relative to other activities in Canada.
CO ₂	Waste	5.C Incineration and Open Burning of Waste / 5.C.2 Open Burning of Waste / 5.C.2.2 Non-biogenic / 5.C.2.2.a Municipal Solid Waste	Open burning at landfills is banned by regulation in provinces and territories. There is anecdotal evidence that open burning does occur in residential settings amounts in mostly rural areas of the country. However, there is currently no up-to-date methodology to estimate these emissions. It is expected that this is not a large source of emissions relative to other activities in Canada.
CO ₂	Waste	5.F Memo Items / 5.F.1 Long-term Storage of C in Waste Disposal Sites	Work is ongoing to incorporate long term storage of C in waste disposal sites.
CO ₂	Waste	5.F Memo Items / 5.F.2 Annual Change in Total Long-term C Storage	Work is ongoing to incorporate long term storage of C in waste disposal sites.
CO ₂	Waste	5.F Memo Items / 5.F.3 Annual Change in Total Long-term C Storage in HWP Waste	Work is ongoing to incorporate long term storage of C in waste disposal sites.
N ₂ O	Agriculture		N ₂ O emissions from indirect sources of non-agricultural origin are not estimated.
N ₂ O	Agriculture	3.D Agricultural Soils / 3.D.1 Direct N ₂ O Emissions From Managed Soils / 3.D.1.2 Organic N Fertilizers / 3.D.1.2.c Other Organic Fertilizers Applied to Soils	The amount of N in Other Organic Fertilizers Applied to Soils is not available.
N ₂ O	Energy	1.B Fugitive Emissions from Fuels / 1.B.1 Solid Fuels / 1.B.1.b Solid Fuel Transformation	The emissions from briquette manufacturing, as a source, has less than 0.05% of total emissions and does not exceed 500 kt CO ₂ eq.
N ₂ O	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Asphalt roofing	N ₂ O emissions are not estimated because no IPCC methodological guidance is provided.
N ₂ O	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Other (please specify) / Other and Undifferentiated	N ₂ O emissions are not estimated because no IPCC methodological guidance is provided.
N ₂ O	Industrial Processes and Product Use	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Road paving with asphalt	N ₂ O emissions are not estimated because no IPCC methodological guidance is provided.
N ₂ O	LULUCF		N ₂ O emissions from indirect sources of non-agricultural and non-LULUCF origin are not estimated as country-specific information is currently not available.
N ₂ O	LULUCF	4.A Forest Land 4.A Forest Land / 4.A.1 Forest Land Remaining Forest Land / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization	Direct N ₂ O emissions associated with loss of soil organic matter in FLFL are not considered to be significant.
N ₂ O	LULUCF	4.A Forest Land / 4.A.2 Land Converted to Forest Land / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization / 4.A.2.1 Cropland converted to forest land	Management-induced changes in soil organic carbon are not available because country-specific activity data is currently unavailable for the time series.
N ₂ O	LULUCF	4.C Grassland 4.C Grassland / 4.C.1 Grassland Remaining Grassland / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization	Management-induced changes in soil organic carbon from GLGL are not available because country-specific activity data is currently unavailable for the time series.
N ₂ O	LULUCF	4.D Wetlands / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Other Wetlands (please specify)	Currently there are no estimates reported under Other wetlands.
N ₂ O	LULUCF	4.E Settlements 4.E Settlements / 4.E.1 Settlements Remaining Settlements / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization	Emissions of N ₂ O from urban trees are not reported as country-specific information on net carbon stock change in soils is not currently available.
N ₂ O	LULUCF	4.E Settlements / 4.E.2 Land Converted to Settlements / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization / 4.E.2.1 Forest land converted to settlements	Management-induced changes in soil organic carbon are not available because country-specific activity data is currently unavailable for the time series.
N ₂ O	LULUCF	4.E Settlements / 4.E.2 Land Converted to Settlements / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization / 4.E.2.3 Grassland converted to settlements	Management-induced changes in soil organic carbon are not available because country-specific activity data is currently unavailable for the time series.

Table A5-1 Summary of GHG Sources and Sinks Not Estimated (cont'd)

GHG	Sector	Source/Sink Category	Explanation
N ₂ O	Waste	5.C Incineration and Open Burning of Waste / 5.C.2 Open Burning of Waste / 5.C.2.1 Biogenic / 5.C.2.1.a Municipal Solid Waste	Open burning at landfills is banned by regulation in provinces and territories. There is anecdotal evidence that open burning does occur in residential settings amounts in mostly rural areas of the country. However, there is currently no up-to-date methodology to estimate these emissions. It is expected that this is not a large source of emissions relative to other activities in Canada.
N ₂ O	Waste	5.C Incineration and Open Burning of Waste / 5.C.2 Open Burning of Waste / 5.C.2.2 Non-biogenic / 5.C.2.2.a Municipal Solid Waste	Open burning at landfills is banned by regulation in provinces and territories. There is anecdotal evidence that open burning does occur in residential settings amounts in mostly rural areas of the country. However, there is currently no up-to-date methodology to estimate these emissions. It is expected that this is not a large source of emissions relative to other activities in Canada.
SF ₆	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
Unspecified mix of PFCs	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
c-C ₃ F ₆	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.
c-C ₄ F ₈	Industrial Processes and Product Use	2.G Other Product Manufacture and Use / 2.G.2 SF ₆ and PFCs from Other Product Use	Emissions and recovery for SF ₆ and PFCs in Other Product Uses is not available. Data collection and significance assessment is in progress.

Note:

"Not Estimated" includes sources and sinks which are considered in the 2006 IPCC Guidelines (IPCC, 2006) but are not considered in this inventory.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Gaseous Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Liquid Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Solid Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Biomass 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars / Gaseous Fuels	1.A.3.b.i Cars	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars / Liquefied Petroleum Gases (LPG)	1.A.3.b.i Cars	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks / Gaseous Fuels	1.A.3.b.ii Light duty trucks	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks / Liquefied Petroleum Gases (LPG) 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks	1.A.3.b.ii Light duty trucks	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses / Gaseous Fuels	1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses / Liquefied Petroleum Gases (LPG)	1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles / Gaseous Fuels 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles	1.A.3.b.iv Motorcycles	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
CH ₄	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles / Liquefied Petroleum Gases (LPG) 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles	1.A.3.b.iv Motorcycles	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CH ₄	1.B Fugitive Emissions from Fuels / 1.B.1 Solid Fuels / 1.B.1.a Coal Mining and Handling / 1.B.1.a.1 Underground Mines / 1.B.1.a.1.ii Post-Mining Activities	1.B.1.a.1.ii Underground Mines – Mining Activities	1.B.1.a.1.i Underground Mines – Mining Activities	Only aggregated emission factors were available.
CH ₄	1.B Fugitive Emissions from Fuels / 1.B.1 Solid Fuels / 1.B.1.a Coal Mining and Handling / 1.B.1.a.2 Surface Mines / 1.B.1.a.2.ii Post-Mining Activities	1.B.1.a.2.ii Surface Mines – Post-Mining Activities	1.B.1.a.2.i Surface Mines – Mining Activities	Only aggregated emission factors were available.
CH ₄	1.B Fugitive Emissions from Fuels / 1.B.2 Oil and Natural Gas and Other Emissions from Energy Production / 1.B.2.a Oil / 1.B.2.a.1 Exploration	1.B.2.a.1 Oil – Exploration	1.B.2.a.2 Oil – Production	Only aggregated data were available.
CH ₄	1.B Fugitive Emissions from Fuels / 1.B.2 Oil and Natural Gas and Other Emissions from Energy Production / 1.B.2.a Oil / 1.B.2.a.5 Distribution of Oil Products	1.B.2.a.5 Oil – Distribution of Oil Products	1.B.2.a.3 Oil – Transport	Only aggregated data were available.
CH ₄	1.B Fugitive Emissions from Fuels / 1.B.2 Oil and Natural Gas and Other Emissions from Energy Production / 1.B.2.b Natural Gas / 1.B.2.b.1 Exploration	1.B.2.b.1 Natural Gas – Exploration	1.B.2.b.2 Natural Gas – Production	Only aggregated data were available.
CH ₄	1.D Memo Items / 1.D.2 Multilateral Operations	1.D.2 Multilateral Operations	1.A.3.a Domestic Aviation and 1.A.3.d Domestic Navigation	Multilateral Operations emissions, if occurring, will be reported in either 1.A.3.a Domestic Aviation or 1.A.3.d Domestic Navigation.
CH ₄	2.B Chemical Industry / 2.B.10 Other (please specify) / Carbon Black Production – N ₂ O Emissions	2.B.8.f Carbon Black	2.B.8.f Carbon Black	Carbon Black CO ₂ and CH ₄ emissions are reported under 2.B.8.f Carbon Black. This node was created to report N ₂ O emissions.
CH ₄	2.B Chemical Industry / 2.B.10 Other (please specify) / Carbon Black Production – N ₂ O Emissions	2.B.8.f	2.B.8.f	Carbon black is reported under 2.B.8.f Carbon Black. This node was created to report N ₂ O emissions.
CH ₄	2.B Chemical Industry / 2.B.10 Other (please specify) / Confidential Petrochemicals – N ₂ O Emissions	2.B.8.a Methanol, 2.B.8.b Ethylene and 2.B.8.d Carbon Black	2.B.8.a Methanol, 2.B.8.b Ethylene and 2.B.8.d Carbon Black or 2.B.8.g Other (Confidential Petrochemicals – CO ₂ and CH ₄ Emissions) when activity data is confidential.	2.B.10 Other (Confidential Petrochemicals – N ₂ O Emissions) CH ₄ emissions are reported under 2.B.8.a Methanol, 2.B.8.b Ethylene and 2.B.8.d Carbon Black or 2.B.8.g Other (Confidential Petrochemicals – CO ₂ and CH ₄ Emissions). This node was created to report aggregated N ₂ O emissions when activity data is confidential.
CH ₄	2.B Chemical Industry / 2.B.10 Other (please specify) / Ethylene Production – N ₂ O Emissions	2.B.8.b Ethylene	2.B.8.b Ethylene	2.B.10 Other (Ethylene Production – N ₂ O Emissions) CH ₄ emissions are reported under 2.B.8.b Ethylene. This node was created to report N ₂ O emissions for ethylene production.
CH ₄	2.B Chemical Industry / 2.B.10 Other (please specify) / Methanol Production – N ₂ O Emissions	2.B.8.a Methanol	2.B.8.a Methanol	2.B.10 Other (Methanol Production – N ₂ O Emissions) CH ₄ emissions are reported under 2.B.8.a Methanol. This node was created to report N ₂ O emissions for methanol production.
CH ₄	2.B Chemical Industry / 2.B.8 Petrochemical and Carbon Black Production / 2.B.8.d Ethylene Oxide	2.B.8 Petrochemical and Carbon Black Production / 2.B.8.d Ethylene Oxide	2.B.8 Petrochemical and Carbon Black Production / 2.B.8.g Confidential Petrochemicals – CO ₂ and CH ₄ Emissions	2.B.8.d Ethylene Oxide CH ₄ emissions are reported in 2.B.8.g Other (Confidential Petrochemicals – CO ₂ and CH ₄ Emissions) to protect confidential activity data.
CH ₄	2.B Chemical Industry / 2.B.8 Petrochemical and Carbon Black Production / 2.B.8.g Other / Other (please specify) / Styrene	2.B.8.g Other	2.B.8.g Confidential Petrochemicals – CO ₂ and CH ₄ Emissions	Styrene is reported under Confidential Petrochemicals – CO ₂ and CH ₄ Emissions to protect confidential activity data.
CH ₄	2.C Metal Industry / 2.C.1 Iron and Steel Production / 2.C.1.a Steel	2.C.1.a	2.C.1.b Pig Iron	2.C.1.a Steel CH ₄ emissions are reported under 2.C.1.b Pig Iron.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
CH ₄	2.C Metal Industry / 2.C.1 Iron and Steel Production / 2.C.1.c Direct Reduced Iron	2.C.1.c	1.A.2.a	2.C.1.c Direct Reduced Iron CH ₄ emissions are reported under category 1.A.2.a Iron and Steel because only aggregated data is available.
CH ₄	2.C Metal Industry / 2.C.1 Iron and Steel Production / 2.C.1.d Sinter	2.C.1.d	1.A.2.a	2.C.1.d Sinter CH ₄ emissions are reported under category 1.A.2.a Iron and Steel because only aggregated data is available.
CH ₄	2.C Metal Industry / 2.C.1 Iron and Steel Production / 2.C.1.e Pellet	2.C.1.e	1.A.2.a	2.C.1.e Pellet CH ₄ emissions are reported under category 1.A.2.a Iron and Steel because only aggregated data is available.
CH ₄	2.C Metal Industry / 2.C.2 Ferroalloys Production	2.C.2	2.C.1.a and 2.C.1.b	2.C.2 Ferroalloys CH ₄ emissions are reported under 2.C.1.a Steel and 2.C.1.b Pig Iron because only aggregated data is available.
CH ₄	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Solvent use	2.D.3 Solvent Use	2.D.3 Other and Undifferentiated	Solvent use is reported under 2.D.3 Other (Other) (Other and Undifferentiated) because only aggregated data is available.
CH ₄	4.A Forest Land / 4.A.1 Forest Land Remaining Forest Land / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CH ₄	4.B Cropland / 4.B.1 Cropland Remaining Cropland / 4(V) Biomass Burning / Controlled Burning / Mineral Soils	Burning of woody biomass in LULUCF, agricultural residue burning in the Agriculture Sector.	Agriculture Sector	Field burning of agricultural crop residues is reported in the Agriculture Sector.
CH ₄	4.B Cropland / 4.B.1 Cropland Remaining Cropland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Burning of woody biomass in LULUCF, agricultural residue burning in the Agriculture Sector.	Agriculture Sector	Field burning of agricultural crop residues is reported in the Agriculture Sector.
CH ₄	4.B Cropland / 4.B.2 Land Converted to Cropland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CH ₄	4.C Grassland / 4.C.1 Grassland Remaining Grassland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	AD do not allow the disaggregation of activity into organic and mineral soils.
CH ₄	4.C Grassland / 4.C.1 Grassland Remaining Grassland / 4(V) Biomass Burning / Wildfires / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CH ₄	4.D Wetlands / 4.D.2 Land Converted to Wetlands / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CH ₄	4.E Settlements / 4(V) Biomass Burning / Organic Soils	4(V) Biomass Burning – Organic soils	4(V) Biomass Burning – Mineral soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CH ₄	4.E Settlements / 4.E.2 Land Converted to Settlements	Table 4, if possible to differentiate	Table 4(V)	Emissions of CH ₄ are reported in Table 4(V) Biomass Burning.
CH ₄	5.B Biological Treatment of Solid Waste / 5.B.1 Composting / 5.B.1.b Other (please specify)	Included under 5.b.1.a as a single value.	Included under 5.b.1.a as a single value.	Included under 5.b.1.a as a single value.
CH ₄	5.B Biological Treatment of Solid Waste / 5.B.2 Anaerobic Digestion at Biogas Facilities / 5.B.2.a Municipal Solid Waste		Included under 5.b.1.a as a single value.	
CH ₄	5.B Biological Treatment of Solid Waste / 5.B.2 Anaerobic Digestion at Biogas Facilities / 5.B.2.b Other (please specify)	Included under 5.b.1.a with composting as total emissions for Biological Treatment of Waste.	Included under 5.b.1.a with composting as total emissions for Biological Treatment of Waste.	Included under 5.b.1.a with composting as total emissions for Biological Treatment of Waste.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Gaseous Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Liquid Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Solid Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Biomass 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars / Gaseous Fuels	1.A.3.b.i Cars	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars / Liquefied Petroleum Gases (LPG)	1.A.3.b.i Cars	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks / Gaseous Fuels	1.A.3.b.ii Light duty trucks	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks / Liquefied Petroleum Gases (LPG)	1.A.3.b.ii Light duty trucks	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses / Gaseous Fuels	1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses / Liquefied Petroleum Gases (LPG) 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles / Gaseous Fuels 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles	1.A.3.b.iv Motorcycles	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles / Liquefied Petroleum Gases (LPG) 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles	1.A.3.b.iv Motorcycles	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
CO ₂	1.B Fugitive Emissions from Fuels / 1.B.2 Oil and Natural Gas and Other Emissions from Energy Production / 1.B.2.a Oil / 1.B.2.a.1 Exploration	1.B.2.a.1 Oil – Exploration	1.B.2.a.2 Oil – Production	Only aggregated data were available.
CO ₂	1.B Fugitive Emissions from Fuels / 1.B.2 Oil and Natural Gas and Other Emissions from Energy Production / 1.B.2.a Oil / 1.B.2.a.5 Distribution of Oil Products	1.B.2.a.5 Oil – Distribution of Oil Products	1.B.2.a.3 Oil – Transport	Only aggregated data were available.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
CO ₂	1.B Fugitive Emissions from Fuels / 1.B.2 Oil and Natural Gas and Other Emissions from Energy Production / 1.B.2.b Natural Gas / 1.B.2.b.1 Exploration	1.B.2.b.1 Natural Gas – Exploration	1.B.2.b.2 Natural Gas – Production	Only aggregated data were available.
CO ₂	1.D Memo Items / 1.D.2 Multilateral Operations	1.D.2 Multilateral Operations	1.A.3.a Domestic Aviation and 1.A.3.d Domestic Navigation	Multilateral Operations emissions, if occurring, will be reported in either 1.A.3.a Domestic Aviation or 1.A.3.d Domestic Navigation.
CO ₂	2.B Chemical Industry / 2.B.10 Other (please specify) / Carbon Black Production – N ₂ O Emissions	2.B.8.f Carbon Black	2.B.8.f Carbon Black	Carbon Black CO ₂ and CH ₄ emissions are reported under 2.B.8.f Carbon Black. This node was created to report N ₂ O emissions.
CO ₂	2.B Chemical Industry / 2.B.10 Other (please specify) / Carbon Black Production – N ₂ O Emissions	2.B.8.f	2.B.8.f	Carbon black is reported under 2.B.8.f Carbon Black. This node was created to report N ₂ O emissions.
CO ₂	2.B Chemical Industry / 2.B.10 Other (please specify) / Confidential Petrochemicals – N ₂ O Emissions	2.B.8.a Methanol, 2.B.8.b Ethylene and 2.B.8.d Carbon Black	2.B.8.a Methanol, 2.B.8.b Ethylene and 2.B.8.c Carbon Black or 2.B.8.g Other (Confidential Petrochemicals – CO ₂ and CH ₄ Emissions) when activity data is confidential.	2.B.10 Other (Confidential Petrochemicals – N ₂ O Emissions) CO ₂ emissions are reported under 2.B.8.a Methanol, 2.B.8.b Ethylene and 2.B.8.d Carbon Black or 2.B.8.g Other (Confidential Petrochemicals – CO ₂ and CH ₄ Emissions). This node was created to report aggregated N ₂ O emissions when activity data is confidential.
CO ₂	2.B Chemical Industry / 2.B.10 Other (please specify) / Ethylene Production – N ₂ O Emissions	2.B.8.b Ethylene	2.B.8.b Ethylene	2.B.10 Other (Ethylene Production – N ₂ O Emissions) CO ₂ emissions are reported under 2.B.8.b Ethylene. This node was created to report N ₂ O emissions for ethylene production.
CO ₂	2.B Chemical Industry / 2.B.10 Other (please specify) / Ethylene Production – N ₂ O Emissions	2.B.8.b Ethylene	2.B.8.b. Ethylene	2.B.10 Other (Ethylene Production – N ₂ O Emissions) CO ₂ emissions are reported under 2.B.8.b Ethylene. This node was created to report N ₂ O emissions for ethylene production.
CO ₂	2.B Chemical Industry / 2.B.10 Other (please specify) / Methanol Production – N ₂ O Emissions	2.B.8.a Methanol	2.B.8.a Methanol	2.B.10 Other (Methanol Production – N ₂ O Emissions) CO ₂ emissions are reported under 2.B.8.a Methanol. This node was created to report N ₂ O emissions for methanol production.
CO ₂	2.B Chemical Industry / 2.B.8 Petrochemical and Carbon Black Production / 2.B.8.f Carbon Black	2.B.8 Petrochemical and Carbon Black Production / 2.B.8.f Carbon Black	2.D.3 Other – Other and Undifferentiated	Carbon Black CO ₂ emissions are reported in 2.D.3 Other and Undifferentiated. Emissions from 2.D.3 Other – Other and Undifferentiated are estimated based on non-energy fuel use by fuel/feedstock type and not by industrial activity. Only aggregated data is available. Refer to Annex 3, Section A.3.3 for further details.
CO ₂	2.B Chemical Industry / 2.B.8 Petrochemical and Carbon Black Production / 2.B.8.f Carbon Black	2.B.8 Petrochemical and Carbon Black Production / 2.B.8.f Carbon Black	2.D.3 Other – Other and Undifferentiated	Carbon Black is reported in 2.D.3 Other and Undifferentiated. Only aggregated data are available.
CO ₂	2.B Chemical Industry / 2.B.8 Petrochemical and Carbon Black Production / 2.B.8.g Other / Other (please specify) / Styrene	Other (please specify) / Styrene	2.D.3 Other – Other and Undifferentiated	Styrene is reported under 2.D.3 Other – Other and Undifferentiated.
CO ₂	2.B Chemical Industry / 2.B.8 Petrochemical and Carbon Black Production / 2.B.8.g Other / Other (please specify) / Styrene	2.B.8.g Other	2.D.3 Other – Other and Undifferentiated	Styrene is reported under 2.D.3 Other – Other and Undifferentiated. Disaggregated data currently not available.
CO ₂	2.C Metal Industry / 2.C.1 Iron and Steel Production / 2.C.1.c Direct Reduced Iron	2.C.1.c	1.A.2.a	2.C.1.c Direct Reduced Iron CO ₂ emissions are reported under category 1.A.2.a Iron and Steel because only aggregated data is available.
CO ₂	2.C Metal Industry / 2.C.1 Iron and Steel Production / 2.C.1.d Sinter	2.C.1.d	1.A.2.a, 2.D.3	2.C.1.d Sinter CO ₂ emissions are reported under categories 1.A.2.a Iron and Steel and 2.D.3 Other (Other and Undifferentiated) because only aggregated data is available.
CO ₂	2.C Metal Industry / 2.C.1 Iron and Steel Production / 2.C.1.e Pellet	2.C.1.e	1.A.2.a, 2.D.3	2.C.1.e Pellet CO ₂ emissions are reported under categories 1.A.2.a Iron and Steel and 2.D.3 Other (Other and undifferentiated) because only aggregated data is available.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
CO ₂	2.C Metal Industry / 2.C.2 Ferroalloys Production	2.C.2	2.C.1.a and 2.C.1.b	2.C.2 Ferroalloys CO ₂ emissions are reported under 2.C.1.a Steel and 2.C.1.b Pig Iron because only aggregated data is available.
CO ₂	2.D Non-energy Products from Fuels and Solvent Use / 2.D.1 Lubricant Use	2.D.1	2.D.3	Lubricant use is reported under 2.D.3 Other (Other) (Other and Undifferentiated) because only aggregated data is available.
CO ₂	2.D Non-energy Products from Fuels and Solvent Use / 2.D.1 Lubricant Use	2.D.3	2.D.3	Lubricant use is reported under 2.D.3 Other (Other) (Other and Undifferentiated) because only aggregated data is available.
CO ₂	2.D Non-energy Products from Fuels and Solvent Use / 2.D.2 Paraffin Wax Use	2.D.2	2.D.3	Paraffin Wax use is reported under 2.D.3 Other (Other) (Other and Undifferentiated) because only aggregated data is available.
CO ₂	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Solvent use	2.D.3 Solvent Use	2.D.3 Other and Undifferentiated	Solvent use is reported under 2.D.3 Other (Other) (Other and Undifferentiated) because only aggregated data is available.
CO ₂	4.A Forest Land / 4.A.1 Forest Land Remaining Forest Land / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CO ₂	4.B Cropland / 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils / Total Organic Soils / Drained Organic Soils	If data are available, under the specific LULUC category, where emissions actually occur	Reported in the Agriculture Sector	AD available do not allow the disaggregation of activity into the specific LULUC category.
CO ₂	4.B Cropland / 4.B.1 Cropland Remaining Cropland / 4(V) Biomass Burning / Controlled Burning / Mineral Soils	Burning of woody biomass in LULUCF, agricultural residue burning in the Agriculture Sector.	Agriculture Sector	Field burning of agricultural crop residues is reported in the Agriculture Sector.
CO ₂	4.B Cropland / 4.B.1 Cropland Remaining Cropland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Burning of woody biomass in LULUCF, agricultural residue burning in the Agriculture Sector.	Agriculture Sector	Field burning of agricultural crop residues is reported in the Agriculture Sector.
CO ₂	4.B Cropland / 4.B.2 Land Converted to Cropland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CO ₂	4.D Wetlands / 4.D.2 Land Converted to Wetlands / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
CO ₂	4.E Settlements / 4(V) Biomass Burning / Organic Soils	4(V) Biomass Burning – Organic soils	4(V) Biomass Burning – Mineral soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
N ₂ O	3.D Agricultural Soils / 3.D.1 Direct N ₂ O Emissions From Managed Soils / 3.D.1.7 Other	Not present in the IPCC 2006 Guidelines	3.D.1.1 Inorganic N Fertilizers / 3.D.1.2.a Animal Manure Applied to Soils / 3.D.1.2.b Sewage Sludge Applied to Soils / 3.D.1.4 Crop Residues	Two country-specific sources/removals of N ₂ O (conservation tillage and irrigation) are reported with emissions from agricultural soils under 3.D.1.1, 3.D.1.2.a, 3.D.1.2.b and 3.D.1.4. As a result of limitations with the current CRF Reporter Software, it is not currently possible to report these country-specific source/sink categories individually.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Gaseous Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Liquid Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Solid Fuels	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco / Biomass 1.AA Fuel Combustion – Sectoral approach / 1.A.2 Manufacturing Industries and Construction / 1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.e Food Processing, Beverages and Tobacco	1.A.2.g.viii Other	Only aggregated data were available.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars / Gaseous Fuels	1.A.3.b.i Cars	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.i Cars / Liquefied Petroleum Gases (LPG)	1.A.3.b.i Cars	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks / Gaseous Fuels	1.A.3.b.ii Light duty trucks	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.ii Light duty trucks / Liquefied Petroleum Gases (LPG)	1.A.3.b.ii Light duty trucks	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses / Gaseous Fuels	1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses / Liquefied Petroleum Gases (LPG) 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.iii Heavy duty trucks and buses	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles / Gaseous Fuels 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles	1.A.3.b.iv Motorcycles	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Gaseous Fuel (Natural Gas) emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles / Liquefied Petroleum Gases (LPG) 1.AA Fuel Combustion – Sectoral approach / 1.A.3 Transport / 1.A.3.b Road Transportation / 1.A.3.b.iv Motorcycles	1.A.3.b.iv Motorcycles	1.A.3.b.v Other / Propane and Natural Gas Vehicles / Other Liquid Fuels / Propane	Propane emissions for Road Transportation are reported under 1.A.3.b.v Propane and Natural Gas Vehicles.
N ₂ O	1.D Memo Items / 1.D.2 Multilateral Operations	1.D.2 Multilateral Operations	1.A.3.a Domestic Aviation and 1.A.3.d Domestic Navigation	Multilateral Operations emissions, if occurring, will be reported in either 1.A.3.a Domestic Aviation or 1.A.3.d Domestic Navigation.
N ₂ O	2.D Non-energy Products from Fuels and Solvent Use / 2.D.3 Other (please specify) / Solvent use	2.D.3 Solvent Use	2.D.3 Other and Undifferentiated	Solvent use is reported under 2.D.3 Other (Other) (Other and Undifferentiated) because only aggregated data is available.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
N ₂ O	4(IV) Indirect N ₂ O Emissions from Managed Soils / Atmospheric Deposition	Agriculture for agricultural soils, under LULUCF for non-agricultural soils	Agriculture for agricultural soils, NE for non-agricultural soils	N ₂ O emissions from volatized N of Managed Soils are reported in the Agriculture Sector. Indirect N ₂ O emissions from Leaching and Runoff of N from fertilizers and other N sources are reported in the Agriculture Sector. N ₂ O emissions associated with nitrogen leaching ad runoff of N mineralised in mineral soils as a result of loss of soil organic carbon in FLFL are considered to be insignificant.
N ₂ O	4(IV) Indirect N ₂ O Emissions from Managed Soils / Nitrogen Leaching and Run-off	Agriculture for agricultural soils, under LULUCF for non-agricultural soils	Agriculture for agricultural soils, NE for non-agricultural soils	N ₂ O emissions from volatized N of Managed Soils are reported in the Agriculture Sector. Indirect N ₂ O emissions from Leaching and Runoff of N from fertilizers and other N sources are reported in the Agriculture Sector. N ₂ O emissions associated with nitrogen leaching ad runoff of N mineralised in mineral soils as a result of loss of soil organic carbon in FLFL are considered to be insignificant.
N ₂ O	4.A Forest Land / 4.A.1 Forest Land Remaining Forest Land / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Inorganic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in the Agriculture Sector	AD available do not allow the disaggregation of activity into this category.
N ₂ O	4.A Forest Land / 4.A.1 Forest Land Remaining Forest Land / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Organic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in the Agriculture Sector	AD available do not allow the disaggregation of activity into this category.
N ₂ O	4.A Forest Land / 4.A.1 Forest Land Remaining Forest Land / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
N ₂ O	4.A Forest Land / 4.A.2 Land Converted to Forest Land / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Inorganic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in Agriculture Sector	AD available do not allow the disaggregation of activity into this category.
N ₂ O	4.A Forest Land / 4.A.2 Land Converted to Forest Land / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Organic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in the Agriculture Sector	AD available does not allow the disaggregation of activity into the specific LULUCF category.
N ₂ O	4.B Cropland / 4.B.1 Cropland Remaining Cropland / 4(V) Biomass Burning / Controlled Burning / Mineral Soils	Burning of woody biomass in LULUCF, agricultural residue burning in the Agriculture Sector.	Agriculture Sector	Field burning of agricultural crop residues is reported in the Agriculture Sector.
N ₂ O	4.B Cropland / 4.B.1 Cropland Remaining Cropland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Burning of woody biomass in LULUCF, agricultural residue burning in the Agriculture Sector.	Agriculture Sector	Field burning of agricultural crop residues is reported in the Agriculture Sector.
N ₂ O	4.B Cropland / 4.B.2 Land Converted to Cropland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
N ₂ O	4.C Grassland / 4.C.1 Grassland Remaining Grassland / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral Soils	AD do not allow the disaggregation of activity into organic and mineral soils.
N ₂ O	4.C Grassland / 4.C.1 Grassland Remaining Grassland / 4(V) Biomass Burning / Wildfires / Organic Soils	Organic Soils	Mineral Soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
N ₂ O	4.D Wetlands / 4.D.1 Wetlands Remaining Wetlands / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization 4.D Wetlands	Table 4(III)	Table 4(II)	Emissions of N ₂ O from land converted to peat extraction are reported in Table 4(II). Emissions and removals from drainage and rewetting and other management of organic and mineral soils.

Table A5-2 Summary of GHG Sources and Sinks Included Elsewhere (cont'd)

GHG	Source/Sink Category	Allocation as per IPCC Guidelines	Allocation used by the Party	Explanation
N ₂ O	4.D Wetlands / 4.D.2 Land Converted to Wetlands / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization / 4.D.2.1 Forest land converted to wetlands	Table 4(III)	Table 4(II)	Emissions of N ₂ O from land converted to peat extraction are reported in Table 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils.
N ₂ O	4.D Wetlands / 4.D.2 Land Converted to Wetlands / 4(III) Direct N ₂ O Emissions from N Mineralization / Immobilization / 4.D.2.5 Other land converted to wetlands	Table 4(III)	Table 4(II)	Emissions of N ₂ O from land converted to peat extraction are reported in Table 4(II) Emissions and removals from drainage and rewetting and other management of organic and mineral soils.
N ₂ O	4.D Wetlands / 4.D.2 Land Converted to Wetlands / 4(V) Biomass Burning / Controlled Burning / Organic Soils	Organic Soils	Mineral soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
N ₂ O	4.E Settlements / 4(V) Biomass Burning / Organic Soils	4(V) Biomass Burning – Organic soils	4(V) Biomass Burning – Mineral soils	Only aggregated AD are available and do not differentiate organic and mineral soils.
N ₂ O	4.E Settlements / 4.E.1 Settlements Remaining Settlements / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Inorganic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in the Agriculture Sector	AD available do not allow the disaggregation of activity into this category.
N ₂ O	4.E Settlements / 4.E.1 Settlements Remaining Settlements / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Organic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in the Agriculture Sector	AD available do not allow the disaggregation of activity into this category.
N ₂ O	4.E Settlements / 4.E.2 Land Converted to Settlements / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Inorganic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in the Agriculture Sector	AD available do not allow the disaggregation of activity into the specific LULUCF category.
N ₂ O	4.E Settlements / 4.E.2 Land Converted to Settlements / 4(I) Direct N ₂ O Emissions from N Inputs to Managed Soils / Organic N Fertilizers	If data are available, under the specific LULUCF category, where emissions actually occur	Reported in the Agriculture Sector	AD available do not allow the disaggregation of activity into the specific LULUCF category.
SF ₆	2.C Metal Industry / 2.C.7 Other (please specify)	2.C.7	2.C.4	Mg Casting is reported under 2.C.4 Magnesium Production as per IPCC guidelines and ERT recommendations.
SF ₆	2.G Other Product Manufacture and Use / 2.G.1 Electrical Equipment / SF ₆	2.G.1 disaggregated from stocks and from disposal	2.G.1 Electrical Equipment / SF ₆ (from stocks)	disaggregation from stocks and from disposal data is not available and the total is reported as "from stocks."

Note:

"Included Elsewhere" includes sources and sinks in this inventory that are allocated to a sector other than that indicated by the 2006 IPCC Guidelines (IPCC, 2006).

ANNEX 6

EMISSION FACTORS

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This annex summarizes the development and selection of emission factors (EF) used to estimate Canada's annual greenhouse gas (GHG) inventory. Details¹ on sector-specific methodological use of these factors are presented in Annex 3.

A6.1. Fuel Combustion

A6.1.1. Natural Gas and Natural Gas Liquids

A6.1.1.1. Carbon Dioxide (CO₂)

CO₂ emission factors for fossil fuel combustion depend primarily on fuel properties such as carbon content, density and heating value and, to a lesser extent, on the combustion technology.

For natural gas, there are two principal types combusted in Canada: marketable fuel (processed for commercial sale) and non-marketable fuel (unprocessed, for internal use). There are regional variations in marketable and non-marketable natural gas use, with nine regions consuming marketable fuel and seven regions consuming non-marketable fuel.

For the period 1990 to 1998, provincial and territorial emission factors for marketable natural gas (Table A6.1–1) were developed using data from the chemical analysis of representative natural gas samples collected in 1998 (McCann, 2000). Both imported and domestic natural gas were included, where applicable, in the mix of gas samples used for chemical analysis.

For the period 2005 to 2018, an industry expert was contracted to work with the natural gas transmission and distribution industry to define provincial natural gas flow networks and to collect historical data. Over 500,000 data points were collected for these years at key points, such as, transmission lines, interprovincial transfer locations, storage locations, import and export sites, and consumer distribution networks, where volumetric flow and composition data was measured and available. Using this data, the emission factors and energy content values of marketable natural gas were updated for the years 2005 to 2020 (Table A6.1–1) to reflect a gradual increase in complex hydrocarbons in the natural gas stream that off-set the approximately 2% decrease in methane over the same time period. Data collected by the contractor underwent further analysis (ECCC, 2021) and this showed that since it was last measured in 1998 the percent methane composition in the natural gas stream had changed in the period from 1999 to 2004. This resulted in a step change in natural gas parameters and emissions from 2004 to 2005. To minimize the effect of this step change, ECCC revised the natural gas parameters for these intermediate years, 1999 to 2004, using a simple linear interpolation.

¹ For details, see the National Inventory Report 1990–2020: Greenhouse Gas Sources and Sinks in Canada online: <http://www.publications.gc.ca/pub?id=9.506002&sl=0>.

Non-marketable natural gas emission factors for Alberta (Table A6.1–2) were updated using over 400,000 raw gas samples, ranging in date from 1913 to 2016, obtained from the Alberta Energy Regulator (AER) by the Energy and Emissions Research Laboratory (EERL) of Carleton University (EERL, 2020). EERL compiled and analysed the data to provide average gas compositions by township. Gas composition data by township were weighted by township-level fuel gas consumption volumes obtained from Petrinex in 2020, to produce annual average CO₂ emission factors for the province.

Generally, non-marketable natural gas emission factors (Table A6.1–2) are higher than those of marketable natural gas (Table A6.1–1) because of their raw/unprocessed nature where complex hydrocarbons are not removed prior to usage. In addition to methane, the composition of marketable and non-marketable natural gas includes ethane, propane, butane, and other more complex hydrocarbons.

CO₂ emission factors (Table A6.1–4) for natural gas liquids (NGL), such as ethane, propane and butane, were developed based on chemical analysis data for marketable fuels (McCann, 2000).

A6.1.1.2. Methane (CH₄)

Emissions of CH₄ from fuel combustion are technology-dependent. Sectoral emission factors (Table A6.1–3 and Table A6.1–4) have been developed based on technologies typically used in Canada. The factors were developed based on a broad review of emission factors for combustion technologies (SGA Energy, 2000). The emission factor for producer consumption of natural gas was developed based on a technology split for the upstream oil and gas industry (CAPP, 1999) and technology-specific emission factors from the U.S. EPA report AP 42 (U.S. EPA, 1996).

A6.1.1.3. Nitrous Oxide (N₂O)

Emissions of N₂O from fuel combustion are technology-dependent. Emission factors (Table A6.1–3 and Table A6.1–4) have been developed based on technologies typically used in Canada. The factors were developed from an analysis of combustion technologies and a review of their emission factors (SGA Energy, 2000).

Table A6.1–1 CO₂ Emission Factors for Marketable Natural Gas

Year(s)	Region – Emission Factors (g/m ³) ^a													
	Canada	BC	AB	SK	MB	QC	ON	NB	NS	PE	NL	YK	NW ^b	NU
1990	1 899	1 926	1 928	1 829	1 886	1 887	1 888	1 901	1 901	1 901	1 901	1 901	2 466	NO
1995	1 899	1 926	1 928	1 829	1 886	1 887	1 888	1 901	1 901	1 901	1 901	1 901	2 466	NO
2000	1 895	1 918	1 923	1 839	1 880	1 880	1 881	1 884	1 884	1 884	1 884	1 900	2 466	1 900
2005	1 883	1 898	1 911	1 864	1 864	1 864	1 865	1 867	1 867	1 867	1 867	1 898	2 466	1 898
2006	1 878	1 896	1 917	1 855	1 855	1 854	1 855	1 862	1 862	1 862	1 862	1 896	2 466	1 896
2007	1 881	1 901	1 910	1 857	1 857	1 858	1 859	1 856	1 856	1 856	1 856	1 901	2 466	1 901
2008	1 887	1 906	1 910	1 863	1 863	1 865	1 865	1 860	1 860	1 860	1 860	1 906	2 466	1 906
2009	1 889	1 900	1 920	1 861	1 861	1 865	1 863	1 865	1 865	1 865	1 865	1 900	2 466	1 900
2010	1 891	1 902	1 923	1 860	1 862	1 868	1 869	1 864	1 864	1 864	1 864	1 902	2 466	1 902
2011	1 893	1 900	1 921	1 866	1 866	1 870	1 871	1 869	1 869	1 869	1 869	1 900	2 466	1 900
2012	1 905	1 899	1 931	1 874	1 873	1 882	1 888	1 873	1 873	1 873	1 873	1 899	1 899	1 899
2013	1 910	1 909	1 933	1 875	1 873	1 884	1 896	1 886	1 886	1 886	1 886	1 909	1 909	1 909
2014	1 912	1 912	1 930	1 878	1 875	1 882	1 896	1 892	1 892	1 892	1 892	1 912	1 912	1 912
2015	1 924	1 939	1 943	1 881	1 905	1 911	1 911	1 900	1 900	1 900	1 900	1 939	1 939	1 939
2016	1 932	1 941	1 954	1 897	1 896	1 907	1 915	1 914	1 914	1 914	1 914	1 941	1 941	1 941
2017	1 936	1 955	1 955	1 900	1 903	1 915	1 916	1 914	1 914	1 914	1 914	1 955	1 955	1 955
2018	1 944	1 966	1 962	1 920	1 915	1 926	1 921	1 918	1 918	1 918	1 918	1 966	1 966	1 966
2019	1 944	1 966	1 962	1 920	1 915	1 926	1 921	1 921	1 921	1 921	1 921	1 966	1 966	1 966
2020	1 944	1 966	1 962	1 920	1 915	1 926	1 921	1 921	1 921	1 921	1 921	1 966	1 966	1 966

Notes:

The term “marketable” applies to fuel consumed by the Utility, Industry, Residential, Commercial, and Transport subsectors.

a. Years 1990–1998, McCann (2000). Years 1999–2021, ECCC (2021).

b. Prior to 2012, natural gas consumption was regional non-marketable natural gas. Since 2012, marketable natural gas has been imported from B.C.

NO = Not occurring

Table A6.1-2 CO₂ Emission Factors for Non-Marketable Natural Gas

Province/Territory	Year(s)	Emission Factor (g/m ³)
AB ^a	1990 to 2009	2 080
	2010	2 054
	2011	2 062
	2012	2 068
	2013	2 071
	2014	2 075
	2015	2 081
	2016	2 089
	2017	2 093
	2018	2 102
	2019	2 107
	2020	2 109
NL	1990 to 2020 ^b	2 494
NS		2 494
NB		NO
QC		NO
ON		NO
MB		NO
SK		2 441
BC		2 162
YK		2 401
NT		2 466

Note:
The term "non-marketable" applies to raw/unprocessed gas consumption, mainly by natural gas producers.

a. Adapted from EERL (2020) using Petrinex (2020) annual volumetric data
b. McCann (2000)

Table A6.1-3 CH₄ and N₂O Emission Factors for Natural Gas

Source	Emission Factor (g/m ³) ^a	
	CH ₄	N ₂ O
Electric Utilities	0.490	0.049
Industrial	0.037	0.033
Producer Consumption (Non-marketable)	6.4 ^b	0.060
Pipelines	1.900	0.050
Cement	0.037	0.034
Manufacturing Industries	0.037	0.033
Residential, Construction, Commercial/Institutional, Agriculture	0.037	0.035

Notes:
a. SGA Energy (2000)
b. Adapted from U.S. EPA (1996) and CAPP (1999)

Table A6.1-4 Emission Factors for Natural Gas Liquids

Source	Emission Factor (g/L)		
	CO ₂	CH ₄	N ₂ O
Propane			
Residential	1 515 ^a	0.027 ^b	0.108 ^b
All Other Uses	1 515 ^a	0.024 ^b	0.108 ^b
Ethane	986 ^a	0.024 ^b	0.108 ^b
Butane	1 747 ^a	0.024 ^b	0.108 ^b

Notes:

a. McCann (2000)
b. SGA Energy (2000)

A6.1.2. Refined Petroleum Products

A6.1.2.1. CO₂

CO₂ emission factors for fossil fuel combustion are dependent primarily on fuel properties and, to a lesser extent, on the combustion technology.

Emission factors have been developed for each major class of refined petroleum products (RPP) based on their heating value, carbon content and density (McCann, 2000), to ensure consistency with the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006).

The composition of petroleum coke is process-specific. Factors have been developed for both refinery (catalytic cracker) derived cokes and coke used in upgrading facilities. These factors (Table A6.1-6) have been developed using emissions and energy content data provided by industry to the Canadian Energy and Emissions Data Centre (CEEDC).² The bulk of the coke consumed by refineries is catalytic cracker-derived, and the emission factor is an average of petroleum coke and catalytic cracker coke emission factors.

Emission factors for still gas (Table A6.1-6) from refining operations and upgrading facilities were also derived from data provided by industry and reported by CEDDC.

A6.1.2.2. CH₄

Emissions of CH₄ from fuel combustion are technology-dependent. Emission factors were developed (Table A6.1-5) based on technologies typically used in Canada. The factors were developed from an analysis of combustion technologies and a review of their emission factors (SGA Energy, 2000).

The emission factor for petroleum coke was assumed to be the same for both catalytic cracker-derived cokes and coke used in upgrading facilities.

The emission factor for still gas from upgraders (Table A6.1-5) was based on the 2006 IPCC default emission factor and was adapted using energy conversion factors published by Statistics Canada (2014). The still gas emission factors for refineries and other industries (Table A6.1-8) were based on the 2006 IPCC default emission factor, which was calculated on an annual basis using energy conversion factors provided by Statistics Canada (2014).

A6.1.2.3. N₂O

Emissions of N₂O from fuel combustion are technology-dependent. Emission factors for RPP, with the exception of petroleum coke, have been developed (Table A6.1-5) based on technologies typically used in Canada. The factors were developed from an analysis of combustion technologies and a review of their emission factors (SGA Energy, 2000).

Emission factors for petroleum coke (Table A6.1-7) were based on 2006 IPCC default emission factors and were calculated on an annual basis using energy conversion factors provided by Statistics Canada (2014).

² Griffin, B. 2020. Personal communication (email from Griffin B., CEDDC to Tracey K., Program Engineer, PIRD dated September 25, 2020). Canadian Energy and Emissions Data Centre (CEDDC).

Table A6.1–5 Emission Factors for Refined Petroleum Products

Source	Emission Factor (g/L)		
	CO ₂ ^a	CH ₄ ^b	N ₂ O ^c
Light Fuel Oil			
Electric Utilities	2 753	0.18	0.031
Industrial	2 753	0.006	0.031
Producer Consumption	2 670	0.006	0.031
Residential	2 753	0.026	0.006
Forestry, Construction, Public Administration and Commercial/Institutional	2 753	0.026	0.031
Heavy Fuel Oil			
Electric Utilities	3 156	0.034	0.064
Industrial	3 156	0.12	0.064
Producer Consumption	3 190	0.12	0.064
Residential, Forestry, Construction, Public Administration and Commercial/Institutional	3 156	0.057	0.064
Kerosene			
Electric Utilities	2 560 ^c	0.006	0.031
Industrial	2 560 ^c	0.006	0.031
Producer Consumption	2 560 ^c	0.006	0.031
Residential	2 560 ^c	0.026	0.006
Forestry, Construction, Public Administration and Commercial/Institutional	2 560 ^c	0.026	0.031
Diesel – Refineries and Others^d			
Diesel – Upgraders ^d	2 681	0.078	0.022
Petroleum Coke	See Table A6.1–6	0.12	See Table A6.1–7
Still Gas – Refineries and Others	See Table A6.1–6	See Table A6.1–8	0.00002
Still Gas – Upgraders	See Table A6.1–6	0.000039	0.00002
Motor Gasoline ^e	2 307	0.100	0.02
Notes:			
a. McCann (2000); except Kerosene, Diesel and Motor Gasoline			
b. SGA Energy (2000); except Diesel and Motor Gasoline			
c. Assumed McCann (2000) aviation turbo-fuel emission factor			
d. CO ₂ from ECCC (2017b); CH ₄ and N ₂ O from Oak Leaf Environmental Inc. (2017)			
e. CO ₂ from ECCC (2017b); CH ₄ and N ₂ O adapted from IPCC (2006)			

Table A6.1–6 CO₂ Emission Factors for Petroleum Coke and Still Gas

	Emission Factor																			
	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	
Petroleum Coke	g/L																			
Upgrading Facilities ^a	3 556	3 551	3 481	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	3 494	
Refineries and Others ^b	3 766	3 790	3 706	3 767	3 778	3 806	3 829	3 836	3 853	3 812	3 828	3 801	3 725	3 749	3 753	3 776	3 737	3 865	3 859	
Still Gas	g/m ³																			
Upgrading Facilities ^a	2 310	2 090	2 120	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	2 140	
Refineries and Others ^b	1 740	1 800	1 680	1 707	1 741	1 749	1 690	1 711	1 825	1 818	1 718	1 738	1 741	1 762	1 781	1 796	1 847	1 849	1 775	
Notes:																				
a. CEEDC (2003)																				
b. Griffin B. 20210. Personal communication (email from Griffin B to Tracey K, Senior Program Engineer, PIRD dated October 5, 2021). Canadian Emissions and Energy Data Centre.																				

Table A6.1–7 N₂O Emission Factors for Petroleum Coke

	Emission Factor											
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001–2020
Petroleum Coke	g/m ³											
Upgrading Facilities ^{a,b}	21.9	22.1	22.3	22.5	22.7	22.7	22.7	23.0	23.5	23.7	24.2	24.0
Refineries and Others ^{a,b}	24.6	24.8	25.0	25.2	25.5	25.5	25.4	25.8	27.0	27.1	27.6	27.5

Notes:

- a. Adapted from IPCC (2006)
b. Energy content from Statistics Canada (2014)

**Table A6.1-8 CH₄ Emission Factors for Still Gas
(Refineries and Others)**

Year	Emission Factor ^a
	g/m ³
1990–96	0.033
1997	0.032
1998	0.031
1999	0.033
2000	0.034
2001	0.034
2002	0.033
2003	0.033
2004	0.033
2005	0.032
2006	0.032
2007	0.032
2008	0.032
2009	0.032
2010	0.032
2011	0.033
2012	0.031
2013	0.031
2014	0.031
2015	0.033
2016	0.032
2017	0.033
2018	0.032
2019	0.032
2020	0.032

Note:

a. Adapted from IPCC (2006) using energy content taken from Griffin B. 2019. Personal communication (email from Griffin B to Tracey K, Senior Program Engineer, PIRD dated Sept 26, 2019). Canadian Emissions and Energy Data Centre.

A6.1.3. Coal and Coal Products

A6.1.3.1. CO₂

CO₂ emission factors for coal combustion depend largely on the properties of the fuel and, to a lesser extent, on the combustion technology. Coal emission factors (Table A6.1-9) were developed for each province on the basis of the rank of the coal and the region of supply. Emission factors were based on data from chemical analysis of coal samples for electric utilities, which account for the vast majority of coal consumption.

Some factors for Canadian bituminous coal presented in Table A6.1-9 were developed based on a statistical analysis, by ECCC (Radovan et al., 2012), of over 3000 analytical samples for a variety of coal types and producing/consuming regions. The analysis and uncertainty calculations were conducted using the @Risk software package. The coal emission factors are presented with uncertainty estimates, since the supply and quality of coal can vary over time. The average coal carbon and moisture content for each coal type was used to develop CO₂ emission factors.

An additional study to determine country-specific coal oxidation factors and further investigate the carbon content of coal burned at electric generation facilities was conducted for ECCC by GHD Limited in 2016 (ECCC, 2017a). Based on an analysis of this study and Radovan et al. (2012), updated emission and oxidation factors as well as uncertainty estimates for many coal-types have been determined. This was expanded on in 2021, when ECCC collected further carbon content coal data from electric generation facilities that did not participate in the 2016 study (ECCC, 2021c).

Factors for anthracite imported from the United States are from Annex 2 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008 (U.S. EPA, 2010). All coal emission factors in Table A6.1-9 now incorporate Canada-specific oxidation factors (ECCC, 2017a).

Table A6.1–9 CO₂ Emission Factors for Coal

Province	Coal Type	Source	Emission Factor (kg CO ₂ / tonne) ^{a,b,c,d}			Moisture (wt %)	
			Mean	Uncertainty (95% CI)			
			Low	High			
NL, PE (Prior to 2000)	Canadian Bituminous ^b	NS	2 315	-33%	22%	3.2	
NL, PE (2000 onward)	Canadian Bituminous ^b	AB	2 185	-26%	26%	7.7	
QC (Prior to 2000)	Canadian Bituminous ^b	NS	2 329	-33%	22%	3.2	
QC (2000 onward)	Canadian Bituminous ^b	AB	2 198	-26%	26%	7.7	
NS	Canadian Bituminous ^b	NS	2 329	-33%	22%	3.2	
NB (Prior to 2010)	Canadian Bituminous ^b	NB	2 319	-14%	14%	3.2	
NB (2010, 2011, 2013, 2014)	Sub-bituminous ^c	Foreign	2 185	-2%	2%	19	
NB (2012, 2015 onward)	Sub-bituminous ^c	Foreign	2 349	-2%	2%	12	
ON, AB, SK, BC	Canadian Bituminous ^b	AB	2 198	-26%	26%	7.7	
NB, NS, PE and NL	Foreign Bituminous ^b	Non-U.S.	2 540	-7%	7%	8.3	
ON, MB	Foreign Bituminous ^c	U.S. (Pennsylvania)	2 651	-7%	7%	N/A	
QC, AB, BC	Foreign Bituminous ^c	U.S. (Pennsylvania)	2 662	-7%	7%	N/A	
All Provinces and Territories, except SK	Lignite ^c	SK	1 462	-13%	13%	24	
SK	Lignite ^c	SK	1 457	-13%	13%	36	
QC, ON, MB, NB, NS, PE	Sub-bituminous ^c	Foreign	1 865	-8%	8%	24	
AB, SK, BC	Sub-bituminous ^c	AB	1 763	-11%	11%	21	
All Provinces and Territories	Anthracite	--	2 382	-6%	6%	N/A	

Notes:
CI = confidence interval
N/A = Not available
a. Factors presented on a “wet basis.” Moisture content shown is that for the “weighted average” emission factor.
b. Carbon content, Radovan et al. (2012), oxidation factor, ECCC (2019).
c. Carbon content and oxidation factor, ECCC (2019).
d. 95% Confidence Intervals, which were determined through statistical analysis of Canadian coal data.

Table A6.1–10 CO₂ Emission Factors for Coal Products

Coal Product – Fuel Type	Emission Factor
Coke Oven Gas ^a	687 g/m ³
Coke ^b	3 173 g/kg

Notes:
a. McCann (2000)
b. CRA (2014)

Coke and coke oven gas emission factors are presented in Table A6.1–10. The coke emission factor was developed from an iron and steel industry study completed in 2014 (CRA, 2014). It is representative of coke use in the cement, non-ferrous metal and other manufacturing industries. The coke oven gas emission-factor value is from McCann (2000) and represents use in the iron and steel industry.

A6.1.3.2. CH₄

Emissions of CH₄ from fuel combustion are technology-dependent. Emission factors for sectors (Table A6.1–11) have been developed based on technologies typically used in Canada. The factors were developed from an analysis of combustion technologies and a review of their emission factors (SGA Energy, 2000).

A6.1.3.3. N₂O

Emissions of N₂O from fuel combustion are technology-dependent. Emission factors for sectors (Table A6.1–11) have been developed based on technologies typically used in Canada. The emission factors were developed from an analysis of combustion technologies and a review of their emission factors (SGA Energy, 2000).

Table A6.1–11 CH₄ and N₂O Emission Factors for Coal

Source	Emission Factor	
	CH ₄	N ₂ O
	g/kg	
Coal		
Electric Utilities	0.02	0.03
Industry and Heat & Steam Plants	0.03	0.02
Residential, Public Administration	4.00	0.02
Coke	0.03	0.02
	g/m ³	
Coke Oven Gas	0.04	0.04

Note: Source = SGA Energy (2000)

A6.1.4. Fugitive Emission Factors for Coal Mining

The factors in Table A6.1–12 are for fugitive emissions from coal mining only. Although derived from measurements at individual mines or coal seams, these emission factors are aggregated and weighted, province-wide averages for a given mine type. These weighted emission factors are updated yearly to account for the change in production of particular coal types, at individual mines. They should be applied to total gross (not net) quantities of coal mined which includes small quantities of minerals, stone and other inert materials mined with the coal, but later removed before sale or consumption.

Table A6.1–12 Fugitive Emission Factors for Coal Mining

Area	Coal Type	Mine Type	Emission Factor	Units
NS	Bituminous	Surface	0.07	t CH ₄ /kt coal mined
NS	Bituminous	Underground	14.5	t CH ₄ /kt coal mined
NS	Bituminous	Surface	0.07	t CH ₄ /kt coal mined
SK	Lignite	Surface	0.07	t CH ₄ /kt coal mined
AB	Bituminous	Surface	0.67	t CH ₄ /kt coal mined
AB	Bituminous	Underground	1.69	t CH ₄ /kt coal mined
AB	Sub-bituminous	Surface	0.21	t CH ₄ /kt coal mined
BC	Bituminous	Surface	0.93	t CH ₄ /kt coal mined
BC	Bituminous	Underground	2.78	t CH ₄ /kt coal mined

Note: Adapted from King (1994), and Cheminfo and Clearstone Engineering Ltd (2014).

A6.1.5. Other Fuels

A6.1.5.1. CO₂

Alternative fuels such as tires, refuse, and waste oil and solvents are used in the cement industry to offset combustion of purchased fuels like coal, oil or natural gas. CO₂ emissions associated with the stationary combustion of waste fuels are included in the National Inventory Report where data are available. Fuel use data reported by the cement industry, using CO₂ accounting and reporting standards developed by the World Business Council for Sustainable Development (WBCSD, 2005), were used to generate the emission factors in Table A6.1–13.

Some municipal solid wastes and medical wastes are combusted in waste-to-energy facilities. See A6.7.2 for the emission factors associated with these other fuels.

Table A6.1-13 Emission Factors for Alternative Fuels

Source/Fuel	GHG	Emission Factor (kg/GJ)												
		1990–1994	1995–2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011–2020
Cement Industry Waste Fuel	CO ₂ ^a	78.8	77.6	78.6	80.6	82.6	81.5	81.2	83.8	87.7	86.3	79.2	80.1	81.5
	CH ₄ ^b	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	N ₂ O ^b	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004

Notes:

a. Adapted from WBSCD (2005)

b. Adapted from IPCC (2006)

A6.1.5.2. CH₄

CH₄ emission factors for alternative fuels were adapted from the 2006 IPCC Guidelines (IPCC, 2006).

Some municipal solid wastes and medical wastes are combusted in waste-to-energy facilities. See Annex A6.7.2 for the emission factors associated with these other fuels.

A6.1.5.3. N₂O

N₂O emission factors for alternative fuels were adapted from the 2006 IPCC Guidelines (IPCC, 2006).

Some municipal solid wastes and medical wastes are combusted in waste-to-energy facilities. See Annex A6.7.2 for the emission factors associated with these other fuels.

A6.1.6. Mobile Combustion

A6.1.6.1. CO₂

CO₂ emission factors for mobile combustion are dependent on fuel properties and are generally the same as those used for stationary combustion fuels.

A6.1.6.2. CH₄

Emissions of CH₄ from fuel combustion are technology-dependent. Mode-specific CH₄ emission factors have been developed based on technologies typically used in Canada, and are summarized in Table A6.1–14. The factors were initially adopted from a review of available knowledge and an analysis of combustion technologies. A number of on-road CH₄ emission factors were subsequently refined with updated Canadian and U.S. emissions test results (Environment Canada, 2006, 2009; Graham et al., 2008).

Over 50 aircraft-specific aviation turbo fuel CH₄ emission factors from the 2006 IPCC Guidelines (IPCC, 2006) are used in the Tier 3 civil aviation model (Aviation Greenhouse Gas Emission Model—AGEM). Table A6.1–14 displays a national overall average implied emission factor (refer to section A3.4.2.3 for more information on AGEM).

A6.1.6.3. N₂O

Emissions of N₂O from fuel combustion are technology-dependent. Mode-specific N₂O emission factors have been developed based on technologies typically used in Canada. The factors were initially adopted from a review of available knowledge and an analysis of combustion technologies. A number of on-road N₂O emission factors were subsequently refined with updated Canadian and U.S. emissions test results (Environment Canada, 2006, 2009; Graham et al., 2008, 2009).

In particular, the updated test data highlighted the effect of high-sulphur gasoline on N₂O emission factors. Vehicles fuelled with high-sulphur gasoline for the majority of their useful lives generally emitted higher levels of N₂O than those run on low-sulphur gasoline (Environment Canada, 2009).

Table A6.1-14 Emission Factors for Energy Mobile Combustion Sources

Mode [†]	Emission Factors (g/L fuel)		
	CO ₂	CH ₄	N ₂ O
Road Transport			
Gasoline Vehicles			
Light-duty Gasoline Vehicles (LDGVs)			
Tier 2	2 307.3 ^a	0.14 ^c	0.022 ^d
Tier 1	2 307.3 ^a	0.23 ^e	0.47 ^e
Tier 0	2 307.3 ^a	0.32 ^f	0.66 ^g
Oxidation Catalyst	2 307.3 ^a	0.52 ^h	0.20 ^f
Non-catalytic Controlled	2 307.3 ^a	0.46 ^h	0.028 ^f
Light-duty Gasoline Trucks (LDGTs)			
Tier 2	2 307.3 ^a	0.14 ^c	0.022 ^d
Tier 1	2 307.3 ^a	0.24 ^e	0.58 ^e
Tier 0	2 307.3 ^a	0.21 ^h	0.66 ^g
Oxidation Catalyst	2 307.3 ^a	0.43 ^h	0.20 ^f
Non-catalytic Controlled	2 307.3 ^a	0.56 ^f	0.028 ^f
Heavy-duty Gasoline Vehicles (HDGVs)			
Three-way Catalyst	2 307.3 ^a	0.068 ^h	0.20 ^h
Non-catalytic Controlled	2 307.3 ^a	0.29 ^f	0.047 ^f
Uncontrolled	2 307.3 ^a	0.49 ^f	0.084 ^f
Motorcycles			
Non-catalytic Controlled	2 307.3 ^a	0.77 ^c	0.041 ^c
Uncontrolled	2 307.3 ^a	2.3 ^f	0.048 ^f
Diesel Vehicles			
Light-duty Diesel Vehicles (LDDVs)			
Advanced Control*	2 680.50 ^a	0.051 ^f	0.22 ^f
Moderate Control	2 680.50 ^a	0.068 ^f	0.21 ^f
Uncontrolled	2 680.50 ^a	0.10 ^f	0.16 ^f
Light-duty Diesel Trucks (LDDTs)			
Advanced Control*	2 680.50 ^a	0.068 ^f	0.22 ^f
Moderate Control	2 680.50 ^a	0.068 ^f	0.21 ^f
Uncontrolled	2 680.50 ^a	0.085 ^f	0.16 ^f
Heavy-duty Diesel Vehicles (HDDVs)			
Advanced Control	2 680.50 ^a	0.11 ⁱ	0.151 ⁱ
Moderate Control	2 680.50 ^a	0.14 ^f	0.082 ^f
Uncontrolled	2 680.50 ^a	0.15 ^f	0.075 ^f
Natural Gas Vehicles	1.9 ^b	9E-03 ^f	6E-05 ^f
Propane Vehicles	1 515 ^b	0.64 ^f	0.028 ^f
Off-road			
Off-road Gasoline 2-stroke	2 307.3 ^a	10.61 ⁱ	0.013 ^m
Off-road Gasoline 4-stroke	2 307.3 ^a	5.08 ⁱ	0.064 ^m
Off-road Diesel < 19kW	2 680.50 ^a	0.073 ⁱ	0.022 ⁱ
Off-road Diesel ≥ 19kW, Tier 1 - 3	2 680.50 ^a	0.073 ⁱ	0.022 ⁱ
Off-road Diesel ≥ 19kW, Tier 4	2 680.50 ^a	0.073 ⁱ	0.227 ⁱ
Off-road Natural Gas	1.9 ^b	0.0088 ^f	0.00006 ^f
Off-road Propane	1 515 ^b	0.64 ^f	0.087 ⁱ
Railways			
Diesel Train	2 680.50 ^a	0.149 ^m	1.029 ^m
Marine			
Gasoline	2 307.3 ^a	0.21931 ^m	0.06266 ^m
Diesel	2 680.50 ^a	0.25193 ^m	0.07198 ^m
Light Fuel Oil	2 753 ^b	0.2555 ^m	0.073 ^m
Heavy Fuel Oil	3 156 ^b	0.2856 ^m	0.0816 ^m
Kerosene	2 559.70 ⁿ	0.2471 ^m	0.0706 ^m
Aviation			
Aviation Gasoline	2 325.40 ^j	2.19 ^j	0.23 ^j
Aviation Turbo Fuel	2 559.70 ^b	0.029 ^k	0.0711 ^m
Renewable Fuels			
Ethanol	1 508.04 ^{a, o}	**	**
Biodiesel	2 472.2 ^{a, o, p}	***	***
Notes:			
† In the context of Transportation Modes, Tiers refer to increasingly stringent emission standards, enabled through advancements in emission control technologies. It should not be confused with IPCC GHG estimation methodologies.	a. ECCC (2017b) b. McCann (2000) c. Adapted from Environment Canada (2006) d. Adapted from Environment Canada (2006) and Graham et al. (2009) e. Adapted from Environment Canada (2009) f. SGA Energy (2000) g. Adapted from Barton & Simpson (1994) h. ICF Consulting (2004) i. Graham et al. (2008)		
* Advanced control diesel emission factors are used for Tier 2 diesel vehicle populations.	j. Jaques (1992) k. National overall average emission factor for the whole time series based on 2006 IPCC Guidelines (IPCC 2006). Refer to section A3.1.4.2.3 of Annex 3.1 for further information. l. Oak Leaf Environmental Inc (2017) m. IPCC (2006) Converted into g/L using gross calorific value where necessary. n. Assumed McCann (2000) aviation turbo-fuel emission factor. o. Refer to section 3.5.1 Chapter 3 for further information. p. BioMer (2005)		
** Gasoline CH ₄ and N ₂ O emission factors (by mode and technology) are used for ethanol.			
*** Diesel CH ₄ and N ₂ O emission factors (by mode and technology) are used for biodiesel.			

A6.2. Industrial Processes

A6.2.1. Mineral Products

Emission factors used to estimate emissions from the production and use of mineral products are listed in Table A6.2–1.

Table A6.2–1 Range of CO₂ Emission Factors for Mineral Products

Category	Mineral Product	Emission Factor (g CO ₂ / kg of mineral product)
Cement Production	Clinker	520–533 ^a
	Total Organic Carbon (TOC)	10.6–12.2 ^a
Lime Production	High-Calcium Lime	751–755 ^b
	Dolomitic lime	872–889 ^b
Other Limestone and Dolomite Use	Limestone	418 ^c
	Dolomite	468 ^c
Other Uses of Soda Ash	Soda Ash	415 ^c
Non-Metallurgical Magnesia Production	Magnesite	522 ^c

Notes:

a. Range of year-specific emission factors provided by the Cement Association of Canada (2015) and ECCC (2021).

b. Range of year-specific emission factors developed based on information from the Canadian Lime Institute (CLI) (2008) and ECCC (2021).

c. AMEC Earth & Environmental (2006)

A6.2.2. Chemical Industry

Table A6.2–2, Table A6.2–3, Table A6.2–4 and Table A6.2–5 present the emission factors used for categories included under the Chemical Industry subsector, as well as the sources from which these factors were obtained.

Table A6.2–2 Emission Factors for Ammonia Production

	Average Ammonia-to-Feed Fuel Factor ^a m ³ natural gas / tonne of NH ₃	Emission Factor g CO ₂ / m ³ of natural gas	Emission Recovery Factor g CO ₂ / kg of urea
Ammonia Production	671	Marketable natural gas emission factors found in NIR Table A6.1–1 are used.	728

Note:

a. Facility-specific fuel factors are used and these are confidential.

Table A6.2–3 N₂O Emission Factors for Nitric Acid and Adipic Acid Production

Category	Process Description	N ₂ O Emission Factor (kg N ₂ O / t product)
Nitric Acid Production ^a	High-pressure plants with non-selective catalytic reduction	0.66 ^b
Adipic Acid Production	Oxidation reaction of cyclohexanone and cyclohexanol mixture without N ₂ O abatement	300 ^c

Notes:

a. Emission factors for other nitric acid production process types and abatement technologies are confidential.

b. Collis G. 1992. *Estimates of Nitrous Oxide (N₂O) Emissions from Canadian Nitric Acid Industry*. Personal communication (letter from Collis G to Jaques A, Greenhouse Gas Division, dated March 23, 1992). Canadian Fertilizer Institute.

c. IPCC (2000)

Table A6.2–4 Emission Factors for Petrochemical Products

Petrochemical Product	Emission Factor	Type
Silicon Carbide	11.6 kg CH ₄ / t (tonne) product	IPCC default ^a
Calcium Carbide	4.8 kg CH ₄ / t product	Derived from CH ₄ emission factor for silicon carbide and the ratio of IPCC default Calcium Carbide CO ₂ emission factor to IPCC default Silicon Carbide CO ₂ emission factor (i.e. 11.6 (kg CH ₄ / t SiC) * (1.09 tCO ₂ / tCaC ₂ / 2.62 tCO ₂ / tSiC))
Carbon Black	1.29 kg CH ₄ / t product	Sector-wide weighted average ^b
	0.032 kg N ₂ O / t product	Sector-wide weighted average ^b
Ethylene	0.039 kg CH ₄ / t product	Sector-wide weighted average ^b
	0.0055 kg N ₂ O / t product	Sector-wide weighted average ^b
	0.411 t CO ₂ / t product	Sector-wide weighted average ^c
Ethylene Dichloride	0.0142 kg CH ₄ / t product	IPCC default ^d
Ethylene Oxide	0.5202 t CO ₂ / t product	Sector-wide average ^b
	1.79 kg CH ₄ / t product	IPCC default ^d
Styrene	4 kg CH ₄ / t product	IPCC default ^a
Methanol	0.031 kg CH ₄ / t product	Sector-wide weighted average ^b
	0.010 kg N ₂ O / t product	Sector-wide weighted average ^b
	0.790 t CO ₂ / t product	Sector-wide weighted average ^c
Other Uses of Urea	0.733 t CO ₂ / t product use	IPCC default ^d

Notes:

- a. Default value from IPCC/OECD/IEA (1997)
- b. Cheminfo Services (2010)
- c. Cheminfo Services (2015); emission factors may vary if changes are made to the composition of feed.
- d. IPCC (2006)

Table A6.2–5 Emission Factor for By-Product Emissions from Fluorochemical Production

Process	Emission Factor
HCFC-22 production	0.04 t HFC-23 emitted / t HCFC-22 produced ^a

Note:

- a. IPCC (2006)

A6.2.3. Metal Production

The range of the metallurgical coke emission factors and other parameters used for estimating emissions from Iron and Steel Production are found in Table A6.2–6, Table A6.2–7 and Table A6.2–8.

Tier 1-type emission factors for the category of Aluminium Production and the sources from which these emission factors were obtained are shown in Table A6.2–8.

Table A6.2–6 Range of CO₂ Emission Factors for the Iron and Steel Industry

Parameter	Emission Factor	Unit
Iron ore reduction with coke	3.1–3.3 ^a	t CO ₂ / t (tonne) coke used
Electrode consumption in electric arc furnaces	4.5–7.8 ^b	kg CO ₂ / t steel
Electrode consumption in basic oxide furnaces	0.2–0.9 ^b	kg CO ₂ / t steel
Limestone use	418 ^c	CO ₂ / kg CaCaO ₃
Dolomite use	468 ^c	CO ₂ / kg MgCO ₃

Notes:

a. Range of year-specific emission factors provided in Cheminfo Services (2010) and ECCC (2021).

b. Provided by the Canadian Steel Producers Association and ECCC (2021). Chan K. (2009). Personal communication (email from Chan K to Pagé M, Environment Canada, dated July 21, 2009). Canadian Steel Producers Association.

c. AMEC Earth & Environmental (2006)

Table A6.2–7 Range of Carbon Contents for the Iron and Steel Industry

Parameter	Carbon Contents (%) ^a
Pig iron (production of pig iron) from BFs and DRI plants	3.9–4.7
Pig iron (includes hot metal, cold iron, DRI and pig iron) for steel making	3.2–3.9
Crude steel produced in BOF	0.1–0.13
Crude steel produced in EAF	0.14–0.34
Scrap steel	0.1–0.8

Note:

a. Range of values from CSPA (2009) and ECCC (2021).

Table A6.2–8 Tier 1 Emission Factors for Aluminium Production

Cell Technology Type	Emission Factors (kg / t product)		
	CO ₂	Carbon Tetrafluoride (CF ₄)	Carbon Hexafluoride (C ₂ F ₆)
Side-worked pre-baked	1 600	1.6	0.4
Centre-worked pre-baked	1 600	0.4	0.04
Horizontal stud Söderberg	1 700	0.4	0.03
Vertical stud Söderberg	1 700	0.8	0.04

Note:

a. Data Source = International Aluminium Institute (IAI) (2006)

A6.2.4. Non-Energy Products from Fuels and Solvent Use

The use of fossil fuels as feedstock or for other non-energy use (NEU) may result in emissions during the life of manufactured products. To estimate CO₂ emissions from NEU of natural gas, an emission factor of 38 g CO₂/m³ was used. This emission factor excludes the feedstock use of natural gas to produce ammonia, and it is derived from the NEU of natural gas data found in the 2005 Cheminfo Study (Cheminfo Services, 2005).

Table A6.2–9 shows the emission factors used to develop CO₂ emission estimates for non-energy applications of natural gas liquids and petroleum products, respectively. The emission factors for NEU petroleum coke are found in Table A6.1–5. The 2011 emission factor value for Upgrading Facilities in Table A6.1–5 has been used for Ontario across the time series. For the other provinces, the 2011 emission factor value for Refineries and Others is used across the time series. The emission factors associated with NEU of coal are referenced in Table A6.1–8.

Table A6.2–9 CO₂ Emission Factors for Non-Energy Use of Natural Gas Liquids and Petroleum Products

Product	Fraction of Carbon Stored in Product	CO ₂ Emission Factor (g CO ₂ / L)
Natural Gas Liquids		
Propane	0.8 ^a	303 ^b
Butane	0.8 ^a	349 ^b
Ethane	0.8 ^a	197 ^b
Petroleum Products		
Petrochemical Feedstocks ^c	0.8 ^a	500 ^d
Naphthas ^e	0.75 ^a	625 ^d
Lubricating Oils and Greases ^f	0.2 ^g	2 260 ^d
Petroleum Used for Other Products ^h	0.5 ^a	1 450 ^d
Notes:		
a.	IPCC/OECD/IEA (1997)	
b.	McCann (2000)	
c.	Carbon factor for Petrochemical Feedstocks is 680 g of carbon per litre (C/L) (Jaques 1992).	
d.	The resulting CO ₂ emission factor is calculated by multiplying the carbon factor for each product by the molecular weight ratio between CO ₂ and carbon (44/12) and by (1-fraction of carbon stored in product).	
e.	Carbon factor for Naphthas is 680 g C/L (Jaques 1992).	
f.	Carbon factor for Lubricating Oils and Greases is 770 g C/L (Jaques 1992).	
g.	IPCC (2006)	
h.	Carbon factor for Petroleum Used in Other Products is 790 g C/L (Jaques 1992).	

A6.2.5. Electronics Industry

The use of perfluorocarbons (PFCs), sulphur hexafluoride (SF₆) and nitrogen trifluoride (NF₃) in integrated circuit or semiconductor manufacturing, electrical environmental testing, gross leak testing and thermal shock testing creates GHG emissions of their respective source gases. The use of PFCs and NF₃ in the integrated circuit or semiconductor manufacturing industry can also lead to by-product PFC emissions. The emission factors for the use of PFCs, SF₆ and NF₃ in the electronics industry are summarized in Table A6.2–10.

Table A6.2–10 Emission Factors for the use of PFCs, SF₆ and NF₃ in the Electronics Industry

Application	GHG Source	IPCC Tier	Emission Rate (%) ^a	By-Product Emission Rate
Integrated Circuit or Semiconductor Manufacturing ^b	CF ₄	T2A	90	N/A
	CF ₄	T2B – CVD	90	N/A
	CF ₄	T2B – Etching	70	N/A
	C ₂ F ₆	T2A	60	0.2 kg CF ₄ / kg C ₂ F ₆
	C ₂ F ₆	T2B – CVD	60	0.1 kg CF ₄ / kg C ₂ F ₆
	C ₂ F ₆	T2B – Etching	40	0.4 kg CF ₄ / kg C ₂ F ₆
	c-C ₄ F ₈	T2A	10	0.1 kg CF ₄ / kg c-C ₄ F ₈ , 0.1 kg C ₂ F ₆ / kg c-C ₄ F ₈
	c-C ₄ F ₈	T2B – Etching	20	0.2 kg CF ₄ / kg c-C ₄ F ₈ , 0.1 kg C ₂ F ₆ / kg c-C ₄ F ₈
	SF ₆	T2A	20	N/A
	NF ₃	T2A	20	0.09 kg CF ₄ / kg NF ₃
	NF ₃	T2B – Etching	20	N/A
Other Emissive Applications	PFCs	T2	50% first year / 50% second year	N/A
Notes:				
N/A = Not available				
a. IPCC (2006)				
b. When available, confidential company/gas/process-specific values are used for the fraction of gas volume fed into process types with emission control technology and the fraction of gas destroyed by the emission control technology (respectively, ai and di in the IPCC Guidelines).				

A6.2.6. Product Uses as Substitutes for Ozone Depleting Substances

The use of halocarbons in various applications, such as air conditioning (AC), refrigeration, aerosols, foam blowing, solvents and fire extinguishing, result in hydrofluorocarbon (HFC) and PFC emissions.

Table A6.2–11 and Table A6.2–12 summarize emission rates used to estimate HFC and PFC emissions, respectively.

Table A6.2–11 HFCs as Ozone Depleting Substance (ODS) Substitute—Assembly, In-Service and End-of-Life Emission Factors (%)

Application/Sub-Application	Assembly ^a	In-Service ^b	End-of-Life ^c	Life Time (years)
Aerosols ^d	0	50% of orginal charge	100% of remaining charge	2
Blowing agent in foams ^d				
Open-cell foam	100	-	-	-
Closed-cell foam	10	4.5	100	23
Air conditioning (equipment manufactured in Canada) ^e				
Air conditioner units in motor vehicles	0.5	10	75	13
Chillers (specify centrifugal or reciprocating)	1	4.7	5	17
Residential (air conditioners, dehumidifiers, etc.)	1	4	20	17
Air conditioning (manufactured elsewhere) ^e				
Air conditioner units in motor vehicles	-	10	75	13
Chillers (specify centrifugal or reciprocating)	-	4.7	5	17
Residential (air conditioners, dehumidifiers, etc.)	-	4	20	17
Refrigeration (equipment manufactured in Canada) ^e				
Commercial transport	1	15	30	13
Commercial and institutional (retail foods, vending machines, etc.)	1	10	30	17
Industrial (warehouses, process equipment, etc.)	1	10	30	17
Residential (freezers, refrigerators)	0.6	0.5	30	15
Other equipment (specify)	1.0	10.8	30	15
Refrigeration (manufactured elsewhere) ^e				
Commercial transport	-	15	30	13
Commercial and institutional (retail foods, vending machines, etc.)	-	10	30	17
Industrial (warehouses, processes, etc.)	-	10	30	17
Residential (refrigerators, freezers, etc.)	-	0.5	30	15
Other equipment (specify)	-	10.1	30	15
Solvent ^d	0	50% of orginal charge	100% of remaining charge	2
Fire suppression/extinguishing systems ^d				
Portable (mobile) systems	-	4	5	18
Total flooding (fixed) systems	-	2	5	18
Miscellaneous ^d	-	50% of orginal charge	100% of remaining charge	2
Other (specify) ^d	-	50% of orginal charge	100% of remaining charge	2

Notes:

- a. Percentage of losses of the HFC charged into new equipment
- b. Release percentage of HFC bank (by application) during operation
- c. Release percentage of HFC bank (by application) during disposal
- d. IPCC (2006)
- e. Environment Canada (2015)

Table A6.2-12 PFCs as Ozone Depleting Substance (ODS) Substitutes—Assembly, In-Service and End-of-Life Emission Factors (%)

Application/Sub-Application	Assembly ^a	In-Service ^b	End-of-Life ^c	Life Time (years)
Air Conditioning				
Mobile A/C	0.35	15	100	12
Residential and Commercial A/C, including Heat Pumps	0.6	5.5	100	15
Foam Blowing Agents				
Closed-Cell Foam	10% of original charge	4.5% of original charge	-	20
Refrigeration				
Industrial Refrigeration including Food Processing and Cold Storage	1.75	16	100	15
Medium and Large Commercial Refrigeration	1.75	22.5	100	15
Solvents	0	50% of original charge	100% of remaining charge	2

Notes:

- a. Percentage of losses of the PFC charged into new equipment
- b. Annual release percentage of PFC bank (by application) during operation
- c. Release percentage of PFC bank (by application) during disposal

Source = IPCC (2006)

A6.3. Other Product Manufacture and Use

The uses of N₂O as an anaesthetic and as a propellant result in N₂O emissions. The emission factors used are shown in Table A6.3-1.

The use of perfluorocarbons (PFCs) in contained applications (such as use as an electrical insulator or as a dielectric coolant) results in PFC emissions. The emission factors used for contained applications are shown in Table A6.3-2.

The use of urea-based diesel exhaust fluid (DEF) in diesel vehicles equipped with selective catalytic reduction (SCR) systems results in CO₂ emissions, the rate of which is dependent on the purity factor of urea in DEF as well as the dosing rate of urea to diesel consumption as per Table A6.3-3.

Table A6.3-1 Emission Factors for N₂O Usage (Medical and Propellant)

Product	Application	N ₂ O Emission Rate (%)
N ₂ O Use	Anaesthetic Usage	100
	Propellant Usage	100

Note: Source = IPCC (2006)

Table A6.3-2 Emission Factor for PFC Emissions from Other Contained Product Uses

Process	PFC Emissions from Other Contained Sources
Assembly	1% of charge
Annual Leakage Rate	2% of stock
Disposal	100% of remaining stock
Product Lifespan	15 years

Note: Source = IPCC (2000)

Table A6.3-3 Emission Factors for Use of Urea in SCR Vehicles

Product	DEF Purity	Dosing Rate
Urea use in SCR Vehicles	32.50%	2% of diesel consumption

Note: Source = IPCC (2006)

A6.4. Agriculture

The sources of agricultural GHGs are enteric fermentation, manure management, field burning of crop residues, agricultural soils (including nitrous oxide emissions from mineralization/immobilization associated with loss/gain of soil organic matter), and agricultural use of lime, urea and other-carbon containing fertilizers. The most significant sources use country-specific Tier 2 methodologies. Carbon dioxide emissions from liming, urea application and other carbon-containing fertilizers are calculated based on the total quantity of carbon (C) contained in these products. Ammonia emissions from synthetic nitrogen (N) application are estimated using a country specific modelling method as noted in Annex 3.4. Finally, indirect emissions from ammonia volatilization and nitrogen leaching are calculated based on the IPCC default emission factors provided in Table A6.4–27.

Those emission factors for agriculture calculated based on country-specific methodologies are described in detail in Annex 3.4. In most cases, annual emission factors by gas presented in this annex represent an overall weighted average, which include a number of underlying factors that influence regional emission rates. Emission estimates are developed using more detailed emission factors, as described in Annex 3.4. For enteric fermentation emissions from cattle, weighted national emission factors and the methodology for generating emission factors are detailed in section A3.4.2.1. In the case of manure management CH₄, the methodology for generating emission factors is described in A3.4.3, and weighted national emission factors are presented in A3.4.3.5. For manure management N₂O emissions, the methodologies for calculating direct and indirect N₂O emissions are described in sections A3.4.4.1 and A3.4.4.2, respectively. Finally, the methodologies for generating N₂O emission factors for direct emissions from agricultural soils and pasture, range and paddock (PRP), are described in A3.4.5.1. Cattle are described using an approach consistent with common reporting format (CRF) tables.³ For enteric fermentation, Dairy Cattle includes only dairy cows, while for manure management and PRP, Dairy Cattle includes dairy cows and dairy heifers.

A compilation of emission factors for agriculture are provided here in Table A6.4–1 to Table A6.4–29.

A6.4.1. Enteric Fermentation

Table A6.4–1 CH₄ Emission Factors (EF) for Enteric Fermentation for Cattle from 1990 to 2020

Year	EF _{(EF)T} (kg CH ₄ head ⁻¹ year ⁻¹) ^a							
	Dairy Cows	Dairy Heifers	Bulls	Beef Cows	Beef Heifers	Heifers for Slaughter ^b	Steers ^b	Calves
1990	115.4	79.4	108.0	105.9	82.5	44.7	41.4	43.8
1995	119.1	78.6	117.2	112.1	85.9	48.8	43.6	43.8
2000	125.4	78.0	121.0	117.5	89.4	53.0	47.8	43.8
2005	125.0	77.2	119.9	114.4	87.0	52.8	46.0	43.6
2010	128.6	76.8	128.5	115.2	87.8	52.8	47.0	43.7
2011	129.2	76.8	127.6	115.0	87.5	52.7	47.4	43.7
2012	129.6	76.8	129.8	115.6	87.6	53.8	48.0	43.7
2013	134.0	76.8	117.1	115.3	87.5	53.7	48.0	43.8
2014	134.1	76.7	121.1	116.3	88.1	53.2	48.1	43.8
2015	135.2	76.7	127.5	120.0	90.7	53.8	48.8	43.8
2016	137.5	76.7	128.0	121.3	91.6	53.9	48.8	43.8
2017	138.1	76.7	130.1	120.8	91.3	53.6	48.4	43.8
2018	139.6	76.7	125.3	120.5	91.2	53.7	48.5	43.8
2019	142.2	76.6	124.0	120.3	91.0	53.9	49.0	43.7
2020	142.9	76.6	123.9	120.3	91.0	54.0	49.0	43.8

Notes:

- a. Enteric emission factors are derived from Boadi et al. (2004b), modified to take into account trends in milk production in dairy cows and carcass weights for several beef cattle categories.
b. Reported as kg head⁻¹ yr⁻¹; however, emissions are calculated based on time to slaughter.

3 Canada's 2021 CRF tables are available online at: <https://unfccc.int/ghg-inventories-annex-i-parties/2021>

Table A6.4-2 Methane Emission Factors (EF) for Enteric Fermentation for Non-Cattle Animals

Non-Cattle Animal Category	Enteric Fermentation EF (kg CH ₄ head ⁻¹ year ⁻¹)
Pigs	
Boars	1.5
Sows	1.5
Pigs < 20 kg	1.5
Pigs 20–60 kg	1.5
Pigs > 60 kg	1.5
Other Livestock	
Sheep	8
Lambs	8
Goats	5
Horses	18
Bison	55
Llamas & Alpacas	8
Elk & Deer	20
Wild Boars	1.5
Fox	N/A
Mink	N/A
Rabbits	N/A
Mules and Asses	10
Poultry	
Chickens	N/A
Hens	N/A
Turkeys	N/A
Notes:	
N/A = Not available	
Data source = IPCC (2006) (Vol. 4: Agriculture, Forestry and Other Land Uses, Table 10.10)	

A6.4.2. Manure Management

Table A6.4-3 Maximum Methane-Producing Potential (B_0) by Animal Category

Animal Category	Maximum CH ₄ -Producing Potential (B_0) (m ³ /kg VS)
Dairy Cattle ^a	0.24
Non-dairy Cattle ^b	0.19
Sheep	0.19
Goats	0.18
Horses	0.3
Swine	0.48
Hens	0.39
Broilers	0.36
Turkeys	0.36
Notes:	
VS = Volatile solids	
a. Dairy cattle include dairy cows and dairy heifers.	
b. The non-dairy cattle value is also used for bison.	
Data source = IPCC (2006) (Vol. 4: Agriculture, Forestry and Other Land Uses, Tables 10A-5 to 10A-9)	

Table A6.4–4 Methane Conversion Factors (MCFs) by Animal Category and Manure Management System

Animal Categories	Liquid Systems (MCF _L)	Solid Storage and Drylot (MCF _{SSD})	Pasture, Range and Paddock (MCF _{PRP})	Other Systems (MCF _O)
Non-Dairy Cattle ^a	0.2	0.02	0.01	0.01
Poultry	0.2	0.015	0.015	0.015
Horses	NA	0.01	0.01	0.01
Goats	NA	0.01	0.01	NA
Sheep	0.2	0.01	0.01	0.01
Lambs	0.2	0.01	0.01	0.01

Notes:
NA = Not applicable
a. Non-dairy cattle values are also used for bison.
Source = IPCC (2006) (Vol. 4: Agriculture, Forestry and Other Land Uses, Tables 10A-5 to 10A-9 – cool climate, average annual temperature 12°C)

Table A6.4–5 Methane Conversion Factors (MCF) for Dairy Cattle and Swine

Manure Management System	Manure Management Subsystem	Crust Formation	MCF
Liquid	Earthen Basin	No crust	0.2
	Earthen Basin	Crust	0.13
	Tank	No crust	0.2
	Tank	Crust	0.13
	Slatted floor	N/A	0.2
Solid	Exercise Yard	N/A	0.01
	Pack	N/A	0.01
	Pile	N/A	0.02
Compost		N/A	0.005
Pasture Range Paddock		N/A	0.01
		N/A	0.01

Notes:
N/A = Not available
Source = IPCC (2006) (Vol. 4: Agriculture, Forestry and Other Land Uses, Table 10.17 – cool climate, average annual temperature 12°C)

Table A6.4–6 Emission Factors (EF) to Estimate CH₄ Emissions from Manure Management for Cattle Subcategories from 1990 to 2020

Year	EF _{(MM)T} (kg CH ₄ head ⁻¹ yr ⁻¹)							
	Dairy Cows	Dairy Heifers ^a	Bulls	Beef Cows	Beef Heifers	Heifers for Slaughter ^b	Steers ^b	Calves
1990	13	8	4.5	4.1	3.2	1.9	1.8	2.2
1995	15	9	4.7	4.3	3.2	2.0	1.9	2.1
2000	20	11	4.7	4.5	3.3	2.1	1.9	2.3
2005	26	12	4.6	4.3	3.1	2.1	1.9	2.4
2010	33	15	5.0	4.4	3.1	2.1	2.0	2.8
2011	35	16	5.0	4.4	3.1	2.1	2.0	2.9
2012	35	16	5.0	4.4	3.1	2.1	2.0	2.9
2013	36	16	4.5	4.3	3.1	2.1	2.0	2.8
2014	36	17	4.7	4.4	3.1	2.1	2.0	2.9
2015	37	17	4.9	4.5	3.2	2.2	2.0	2.9
2016	37	17	4.9	4.5	3.2	2.2	2.0	2.9
2017	38	17	5.0	4.5	3.2	2.1	2.0	2.9
2018	38	17	4.8	4.5	3.2	2.2	2.0	3.0
2019	39	17	4.8	4.5	3.2	2.2	2.0	3.0
2020	39	17	4.8	4.5	3.2	2.2	2.0	3.0

Notes:
a. For dairy heifers, emission factors were estimated using B₀, MCF and manure management systems for dairy cows.
b. Reported as kg head⁻¹ yr⁻¹, but emissions are calculated based on time to slaughter.

Table A6.4–7 Emission Factors (EF) to Estimate CH₄ Emissions from Manure Management for Swine Subcategories from 1990 to 2020

Year	EF _{(MM)T} (kg CH ₄ head ⁻¹ yr ⁻¹)				
	Boars	Sows	Pigs (< 20 kg)	Pigs (20-60 kg)	Pigs (> 60 kg)
1990	7.0	7.3	2.2	4.5	8.3
1995	7.0	7.2	2.2	4.5	8.4
2000	7.0	7.2	2.2	4.5	8.5
2005	7.0	7.1	2.2	4.4	8.5
2010	7.0	7.0	2.2	4.4	8.7
2011	7.0	7.0	2.1	4.3	8.7
2012	7.0	7.0	2.1	4.3	8.8
2013	7.0	7.0	2.1	4.3	8.9
2014	7.0	7.0	2.1	4.3	8.9
2015	7.0	7.0	2.2	4.3	9.0
2016	7.0	7.0	2.1	4.3	9.1
2017	7.0	7.0	2.1	4.3	9.1
2018	7.0	7.0	2.1	4.3	9.1
2019	7.0	7.0	2.2	4.3	9.2
2020	7.0	7.0	2.2	4.3	9.3

Table A6.4–8 2020 CH₄ Emission Factors (EF) for Manure Management for Other Livestock

Non-Cattle Animal Categories	Manure Management Emission Factors EF _(MM) (kg CH ₄ head ⁻¹ yr ⁻¹)
Other Livestock	
Sheep	0.33
Lambs	0.22
Goats	0.32
Horses	2.6
Bison	2.1
Elk and Deer	0.22
Wild Boars ^a	0.56
Foxes	0.68
Mink	0.68
Rabbits	0.08
Mules and Asses	0.76
Poultry	
Chickens	0.03
Hens	0.12
Turkeys	0.10
Note:	
a. Emission factor based on swine VS, assuming 100% solid manure.	

Table A6.4–9 Dairy Cattle and Swine Emission Factors for Manure Nitrogen (N) Lost as N₂O-N by Animal Waste Management Systems

Manure Management System	Manure Management Subsystem	Crust Formation	Emission Factor
Liquid	Earthen Basin	No crust	0
	Earthen Basin	Crust	0.005
	Tank	No crust	0
	Tank	Crust	0.005
	Slatted floor	NA	0.002
Solid	Exercise Yard	NA	0.02
	Pack	NA	0.02
	Pile	NA	0.005
Other	Compost	NA	0.01

Notes:
NA = Not applicable
Source = IPCC (2006) (Vol. 4: Agriculture, Forestry and Other Land Uses, Table 10.21)

Table A6.4–10 Emission Factors (EF) for Manure Nitrogen (N) Lost as N₂O-N by Animal Category and Animal Waste Management Systems

	Liquid Systems (EF _L)	Solid Storage and Drylot (EF _{SSD})	Other Systems (EF _O)
Non-dairy Cattle	0.001	0.02	0.005
Poultry	0.001	0.02	0.005
Sheep and Lambs	0.001	0.02	0.005
Goats	0.001	0.02	0.005
Horses	0.001	0.02	0.005
Mules and Asses	0.001	0.02	0.005
Buffalo	0.001	0.02	0.005

Note:
Source = IPCC (2006) (Vol. 4: Agriculture, Forestry and Other Land Uses, Table 10.21)

Table A6.4–11 Emission Factors (EF) for Manure Nitrogen (N) Lost as N₂O During Storage of Cattle and Swine Manure

	EF (g N ₂ O head ⁻¹ year ⁻¹)				
	1990	2005	2010	2015	2020
Cattle^a					
Dairy Cows ^b	1 268	1 128	956	930	915
Beef Cows	862	999	1 016	1 093	1 101
Bulls	1 305	1 495	1 665	1 641	1 577
Dairy Heifers ^b	938	906	775	745	741
Beef Heifers	680	769	784	838	841
Heifers for Slaughter	320	425	435	458	466
Steers	336	426	439	468	480
Calves	382	383	382	382	378
Swine^c					
Sows	74	29	25	24	24
Boars	95	58	53	58	57
Pigs (<20 kg)	6	2	2	2	2
Pigs (20–60 kg)	26	12	10	10	9
Pigs (>60 kg)	52	25	23	22	22

Notes:

- a. Emission factors are derived from information in Boadi et al. (2004), Marinier et al. (2004) and (2005), and default factors in the 2006 IPCC Guidelines. Derivation of the Tier 2 emission factors is explained in NIR Annex 3.4.
- b. For dairy cows and heifers, nitrogen excretion rates are derived from feed intake information from Lactanet (2021), and manure storage practices are taken from farm management surveys, as described in NIR Annex 3.4.
- c. For swine, nitrogen excretion rates are calculated using default IPCC parameters and country-specific animal mass time series, and manure storage practices are taken from farm management surveys, as described in NIR Annex 3.4.

Table A6.4–12 2020 Emission Factors (EF) for Manure Nitrogen (N) Lost as N₂O During Storage of Non-Cattle and Non-Swine Manure

Livestock Category	Emission Factors (EF) ^a (g N ₂ O head ⁻¹ year ⁻¹)
Poultry	
Turkey	54
Hens	12
Pullets	6
Broiler	11
Other Livestock	
Sheep	45
Goat	139
Buffalo	991
Horse	485
Llama and alpacas	150
Lamb	44
Deer	218
Elk	218
Wild boars	271
Rabbit	149
Mink	95
Fox	250
Mules and Asses	258

Note:

- a. Emission factors are derived from information in Marinier et al. (2004) and (2005), and default factors in the 2006 IPCC Guidelines. Derivation of the Tier 2 emission factors is explained in NIR Annex 3.4.

Table A6.4–13 Emission Factors (EF) for Cattle and Swine Manure Nitrogen (N) Lost Indirectly as N₂O Due to Volatilization and Leaching During Storage

	EF (g N ₂ O head ⁻¹ year ⁻¹)				
	1990	2005	2010	2015	2020
Volatilization^a					
Dairy Cow	258	262	231	217	219
Beef Cow	98	105	108	113	114
Bull	162	162	180	173	167
Dairy Heifers	194	186	165	151	156
Beef Heifers	86	83	85	89	92
Heifers for Slaughter	48	48	51	54	56
Steer	49	58	57	59	62
Calf	46	43	43	42	42
Sow	62	58	51	48	48
Boar	60	54	50	45	42
Pig (<20 kg)	5	5	4	4	4
Pig (20–60 kg)	21	20	18	17	17
Pig (>60 kg)	43	42	38	38	40
Leaching^b					
Dairy Cow	23	15	11	10	9
Beef Cow	0	0	0	0	0
Bull	0	0	0	0	0
Dairy Heifers	16	12	10	9	9
Beef Heifers	0	0	0	0	0
Heifers for Slaughter	0	0	0	0	0
Steer	0	0	0	0	0
Calf	0	0	0	0	0
Sow	1.2	0.2	0.1	0.1	0.1
Boar	1.6	0.7	0.6	0.7	0.7
Pig (<20 kg)	0.10	0.02	0.01	0.01	0.01
Pig (20–60 kg)	0.5	0.1	0.1	0.1	0.1
Pig (>60 kg)	0.9	0.3	0.2	0.2	0.2

Notes:

- a. Indirect N₂O from volatilization is calculated using the climate-specific EF₄ values from Table 11.3 in Volume 4, Chapter 11 of the 2019 Refinement to the 2006 IPCC Guidelines. Volatilization is calculated based on Sheppard et al. (2010), Sheppard et al. (2011b) and Chai et al. (2016). Derivation of the Tier 2 emission factors is explained in NIR Annex 3.4.
- b. A tier 2 method for the calculation of swine and dairy cattle leaching is based on Sheppard et al. (2010), Sheppard et al. (2011b) and Chai et al. (2016). Derivation of the Tier 2 emission factors is explained in NIR Annex 3.4.

Table A6.4–14 Annual Emission Factors (EF) for Cattle and Swine Manure Nitrogen (N) Lost as NH₃ Due to Volatilization During Storage

	EF (kg NH ₃ head ⁻¹ year ⁻¹)				
	1990	2005	2010	2015	2020
Cattle					
Dairy Cow	22	17	14	13	13
Beef Cow	39	67	53	50	49
Bull	4	5	5	4	4
Dairy Heifers	7	6	5	4	4
Beef Heifers	5.7	7	5	6	6
Heifers for Slaughter	2.3	6.1	6.1	5.2	4.8
Steer	4.7	7.6	8.0	8.5	7.9
Calf	17.6	25.7	20.0	18.3	17.9
Swine					
Sow	4.6	7.1	4.8	4.8	4.8
Boar	0.3	0.2	0.1	0.1	0.1
Pig (<20 kg)	1.1	1.7	1.5	1.6	1.7
Pig (20–60 kg)	4.6	7.0	4.1	3.7	3.9
Pig (>60 kg)	9.0	13.5	11.0	12.7	13.7

Note: Volatilization is calculated based on Sheppard et al. (2010), Sheppard et al. (2011b) and Chai et al. (2016). Derivation of the emission factors is explained in NIR Annex 3.4.

Table A6.4–15 2020 Emission Factors (EF) for Manure Nitrogen (N) Lost Indirectly as N₂O Due to Volatilization and Leaching During Storage

Livestock Category	Volatilization Emission Factor (EF) ^a (g N ₂ O head ⁻¹ year ⁻¹)	Leaching Emission Factor (EF) ^b (g N ₂ O head ⁻¹ year ⁻¹)
Poultry		
Turkey	16	0
Hens	4	0
Pullets	2	0
Broiler	3	0
Other Livestock		
Sheep	3	0
Goat	11	0
Buffalo	86	0
Horse	28	0
Llama and alpacas	10	0
Lamb	3	0
Deer	40	0
Elk	40	0
Wild boars	35	0
Rabbit	30	0
Mink	8	0
Fox	21	0
Mules and Asses	16	0

Notes:

a. Indirect N₂O from volatilization is calculated using the climate-specific EF4 values from Table 11.3 in Volume 4, Chapter 11 of the 2019 Refinement to the 2006 IPCC Guidelines. Derivation of the volatilization emission factors is explained in NIR Annex 3.4.

b. Leaching is not calculated as there are no tier 1 leaching factors available in the 2006 IPCC Guidelines.

Table A6.4–16 2020 Emission Factors (EF) for Manure Nitrogen (N) Lost as NH₃ Due to Volatilization During Storage

Livestock Category	Emission Factor (EF) (kg NH ₃ head ⁻¹ year ⁻¹)
Poultry	
Turkey	1.0
Hens	0.3
Pullets	0.1
Broiler	0.2
Other Livestock	
Sheep	0.2
Goat	0.6
Buffalo	12
Horse	2.4
Llama and alpacas	0.7
Lamb	0.2
Deer	2.6
Elk	2.6
Wild boars	3.1
Rabbit	1.7
Mink	0.4
Fox	1.2
Mules and Asses	1.3

Note: Volatilization factors are taken from default parameters in the 2006 IPCC Guidelines. Derivation of the emission factors is explained in NIR Annex 3.4.

A6.4.3. Pasture, Range and Paddock

Table A6.4–17 Emission Factors (EF) for Manure Nitrogen (N) Lost as N₂O From Deposition of Cattle Manure on Pasture, Range and Paddock

Year	EF (g N ₂ O kg-N ⁻¹ year ⁻¹) ^{a, b, c, d}									
	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
1990	0.68	0.68	0.68	8.8	9.5	8.8	9.7	7.5	9.4	0.68
2005	0.68	0.68	0.68	8.8	9.6	8.8	9.7	7.5	9.4	0.68
2010	0.68	0.68	0.68	8.8	9.6	8.8	9.7	7.5	9.4	0.68
2020	0.68	0.68	0.68	8.8	9.5	8.9	9.6	7.5	9.4	0.68

Notes:

- a. Emission factors are derived from Rochette et al. (2014) for eastern Canada, and Lemke et al. (2012) for western Canada.
- b. The proportion of excreted manure deposited on pasture is taken from Marinier et al. (2005), for all livestock except dairy cows and heifers.
- c. The proportion of excreted manure deposited on pasture by dairy cows and heifers is based on a farm size relationship derived from Sheppard et al. (2011a), as described in NIR Annex 3.4.
- d. Derivation of the Tier 2 emission factors is explained in NIR Annex 3.4.

Table A6.4–18 Emission Factors (EF) for Manure Nitrogen (N) Lost Indirectly as N₂O Due to Volatilization and Leaching of Manure Deposited on Pasture, Range and Paddock

Year	EF (g N ₂ O kg-N ⁻¹ year ⁻¹)									
	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
Volatilization^a										
1990	1.6	1.8	1.6	2.9	2.3	2.9	3.0	2.7	2.3	1.6
2005	1.6	1.8	1.7	3.1	2.2	3.2	3.4	3.1	2.8	1.6
2010	1.6	1.8	1.6	3.0	1.9	3.0	3.4	2.8	2.7	1.6
2015	1.6	1.7	1.6	3.0	1.9	3.0	3.3	2.7	2.6	1.6
2020	1.6	2.0	1.6	2.8	2.0	3.0	3.3	2.7	2.5	1.6
Leaching^b										
1990	1.9	1.7	2.1	3.5	3.5	3.5	3.1	3.5	3.4	1.6
2005	1.8	1.7	2.1	3.5	3.5	3.5	3.1	3.5	3.4	1.6
2010	1.8	1.8	2.1	3.5	3.5	3.5	3.1	3.5	3.4	1.6
2015	1.8	1.7	2.1	3.5	3.5	3.5	3.1	3.5	3.4	1.6
2020	1.8	2.1	2.1	3.5	3.5	3.5	3.1	3.5	3.5	1.5

Notes:

- a. For dairy cattle, volatilization is calculated based on Sheppard et al. (2011b) and Chai et al. (2016), and the default climate-specific indirect N₂O emission factors from the 2019 Refinement to the 2006 IPCC Guidelines are used. For all other livestock the IPCC Tier 1 methodology is used to estimate indirect N₂O emission factors from volatilization. Default parameters are used from the 2006 IPCC Guidelines as described in NIR Annex 3.4.
- b. A modified IPCC Tier 1 methodology is used to estimate N₂O emissions from leaching in agricultural soils, as described in NIR Annex 3.4.

Table A6.4–19 Emission Factors (EF) for Manure Nitrogen (N) Lost Indirectly as NH₃ Due to Volatilization of Manure Deposited on Pasture, Range and Paddock

Year	EF (kg NH ₃ kg N ⁻¹ year ⁻¹)									
	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
1990	0.20	0.18	0.19	0.13	0.10	0.13	0.14	0.12	0.10	0.20
2005	0.21	0.19	0.20	0.14	0.10	0.14	0.16	0.14	0.13	0.21
2010	0.21	0.19	0.20	0.14	0.09	0.14	0.15	0.13	0.12	0.21
2020	0.21	0.18	0.20	0.13	0.09	0.13	0.15	0.12	0.11	0.21

Note:

For dairy cattle, volatilization is calculated based on Sheppard et al. (2011b) and Chai et al. (2016). For all livestock except dairy cattle, the IPCC Tier 1 methodology is used to estimate volatilization. Further detail can be found in NIR Annex 3.4.

A6.4.4. Agricultural Soils

Table A6.4-20 Emission Factors (EF) for Crop Residue, Organic and Inorganic Fertilizer Nitrogen (N) Lost as N₂O Following Application to Agricultural Soils

EF (g N ₂ O kg ⁻¹ N applied year ⁻¹)							
	AB	BC	MB	ATL	ON	QC	SK
Organic N							
1990	8.2	7.0	9.3	7.7	15	18	5.1
2000	7.8	7.1	9.1	8.2	16	20	4.7
2005	7.6	7.4	8.7	8.3	16	21	4.3
2010	7.4	7.5	8.7	8.8	16	21	4.0
2015	7.8	8.0	9.1	9.2	17	22	4.1
2020	7.9	9.1	9.1	10	17	23	4.3
Inorganic N							
1990	10	5.7	12	12	19	25	7.9
2000	9.1	5.2	11	13	20	29	7.3
2005	8.8	4.9	11	13	20	29	6.9
2010	8.8	5.3	11	14	20	29	6.7
2015	9.0	5.2	11	14	21	30	6.6
2020	9.2	5.9	11	14	21	31	6.5
Crop Residue N							
1990	8.3	4.9	8.9	8.6	14	15	6.6
2000	8.2	5.7	9.1	9.1	15	18	6.1
2005	8.1	5.4	8.4	9.3	16	21	5.8
2010	7.9	4.9	8.9	10	16	22	5.6
2015	8.3	6.2	9.2	11	16	23	5.6
2020	8.6	5.8	9.4	11	17	25	5.5

Note: Country-specific Tier 2 soil N₂O emission factors are calculated as described in NIR Annex 3.4.

Table A6.4-21 Emission Factors (EF) for Manure Nitrogen (N) Lost as NH₃ from Agricultural Soils

Year	EF (g N ₂ O kg ⁻¹ N year ⁻¹) ^a									
	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
1990	235	211	228	295	267	291	253	293	267	239
2005	236	203	196	264	253	251	241	277	256	236
2010	235	195	190	253	250	243	238	266	247	236
2020	233	190	181	233	250	243	237	264	228	235

Notes:

For dairy cattle and swine, volatilization is calculated based on Sheppard et al. (2010), Sheppard et al. (2011b) and Chai et al. (2016).

For all other livestock the IPCC Tier 1 methodology is used to estimate volatilization. Further detail can be found in NIR Annex 3.4.

Table A6.4–22 Emission Factors (EF) for Manure Nitrogen (N) Lost Indirectly as N₂O Due to Volatilization and Leaching of Manure Applied to Agricultural Soils

	EF (g N ₂ O kg ⁻¹ N applied year ⁻¹)									
	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
Volatilization^a										
1990	1.5	2.7	1.6	5.3	4.8	5.3	4.6	5.3	4.8	1.5
2005	1.5	2.5	1.3	4.8	4.6	4.7	4.4	5.0	4.6	1.5
2010	1.5	2.5	1.3	4.6	4.5	4.5	4.3	4.8	4.6	1.5
2020	1.5	2.8	1.2	4.5	4.5	4.5	4.3	4.8	4.5	1.5
Leaching^b										
1990	1.9	2.3	2.1	3.5	3.5	3.5	3.1	3.5	3.5	1.6
2005	1.8	2.4	2.1	3.5	3.5	3.5	3.1	3.5	3.5	1.6
2010	1.8	2.5	2.1	3.5	3.5	3.5	3.1	3.5	3.5	1.6
2020	1.8	2.8	2.1	3.5	3.5	3.5	3.1	3.5	3.5	1.6

Notes:

- a. For dairy cattle and swine, volatilization is calculated based on Sheppard et al. (2010), Sheppard et al. (2011b) and Chai et al. (2016) and the climate-specific default IPCC indirect N₂O emission factors from the 2019 Refinement to the 2006 IPCC Guidelines are used. For all other livestock the IPCC Tier 1 methodology is used to estimate volatilization. Default parameters are used from the 2006 IPCC Guidelines and 2019 Refinement to the 2006 IPCC Guidelines as described in NIR Annex 3.4.
- b. A modified IPCC Tier 1 methodology is used to estimate N₂O emissions from leaching in agricultural soils, as described in NIR Annex 3.4.

Table A6.4–23 Fraction of N Volatilized (FRAC_{GASM}) as Ammonia Resulting from the Application of Biosolid N to Agricultural Soils

IPCC default emission factor, FRAC _{GASM}	0.21 kg NH ₃ -N volatilized / kg N applied
Note:	
Source = IPCC (2019)	

Table A6.4–24 N₂O Emission Factor for Mid-latitude Cultivation of Organic Soils

IPCC default emission factor for mid-latitude cultivation of organic soils	8.0 kg N ₂ O-N/ha-year
Note:	
Source = IPCC (2006)	

Table A6.4–25 Emission Factors (EF) for Biosolid Nitrogen (N) Lost Indirectly as N₂O Due to Leaching of Biosolids Applied to Agricultural Soils

Leaching^a	EF (g N ₂ O kg ⁻¹ N applied year ⁻¹)							
	AB	BC	MB	ATL ^b	ON	QC	SK	
1990	2.0	1.9	2.1	3.5	3.1	3.4	1.5	
2005	2.0	2.0	2.1	3.5	3.0	3.4	1.5	
2010	2.0	1.9	2.1	3.5	3.0	3.4	1.5	
2020	2.0	1.9	2.1	3.5	3.0	3.4	1.5	

Notes:

N/A = not available

- a. A modified IPCC Tier 1 methodology is used to estimate N₂O emissions from leaching in agricultural soils, as described in NIR Annex 3.4.
- b. ATL = Atlantic Canada (NB, NL, NS, PE)

Table A6.4–26 Fractions of N Volatilized (FRAC_{GASF}) as Ammonia Resulting from the Application of Inorganic N Fertilizer, from Select Years, 1990–2020, at a Provincial Scale

Year	Implied EF (kg NH ₃ -N volatilized/kg inorganic fertilizer N applied)									
	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
1990	0.05	0.07	0.05	0.05	0.07	0.06	0.07	0.05	0.07	0.05
2005	0.05	0.08	0.06	0.05	0.06	0.06	0.07	0.05	0.06	0.05
2010	0.05	0.08	0.05	0.04	0.06	0.06	0.06	0.04	0.06	0.05
2015	0.05	0.07	0.05	0.05	0.06	0.06	0.06	0.04	0.06	0.05
2020	0.05	0.07	0.05	0.05	0.07	0.06	0.06	0.05	0.06	0.05

Table A6.4–27 Indirect N₂O Emissions from Agricultural Soils

Emission factor due to volatilization and redeposition of Nitrogen ^a	Wet climate: 0.014 kg N ₂ O-N/kg N Dry climate: 0.005 kg N ₂ O-N/kg N
Emission factor due to leaching/runoff ^b	0.0075 kg N ₂ O-N/kg N
Note:	
a. Source = IPCC (2019) b. Source = IPCC (2006)	

A6.4.5. Other Sources

Table A6.4–28 CH₄ and N₂O Emissions from Field Burning of Agricultural Residues

CH ₄ emission factor	2.7 g CH ₄ kg ⁻¹ dry matter burnt
N ₂ O emission factor	0.07 g N ₂ O kg ⁻¹ dry matter burnt
Note:	
Source = IPCC (2006)	

Table A6.4–29 CO₂ Emissions from Liming and Urea Fertilization

Dolomite emission factor	0.13 Mg C / Mg dolomite applied
Limestone emission factor	0.12 Mg C / Mg limestone applied
Urea emission factor	0.20 Mg C / Mg urea
Note:	
Source = IPCC (2006)	

A6.5. Land Use, Land-Use Change and Forestry

The IPCC Tier 2 and Tier 3 methods and country-specific parameters are used for generating estimates for most of the LULUCF sector. The CBM-CFS3 model is used for estimating growth, litter fall, tree mortality and decomposition, as well as the effects of natural disturbances for Forest Land and the emissions due to forest conversion to other land uses. For Cropland, a process model (CENTURY) is used for estimating CO₂ emissions and removals as influenced by management activities, based on the National Soil Database of the Canadian Soil Information System.⁴ More details on methods, emission factors and parameters for Forest Land, forest conversion and Cropland are provided in Annex 3.5 of this report, specifically in sections A3.5.2 and A3.5.4.

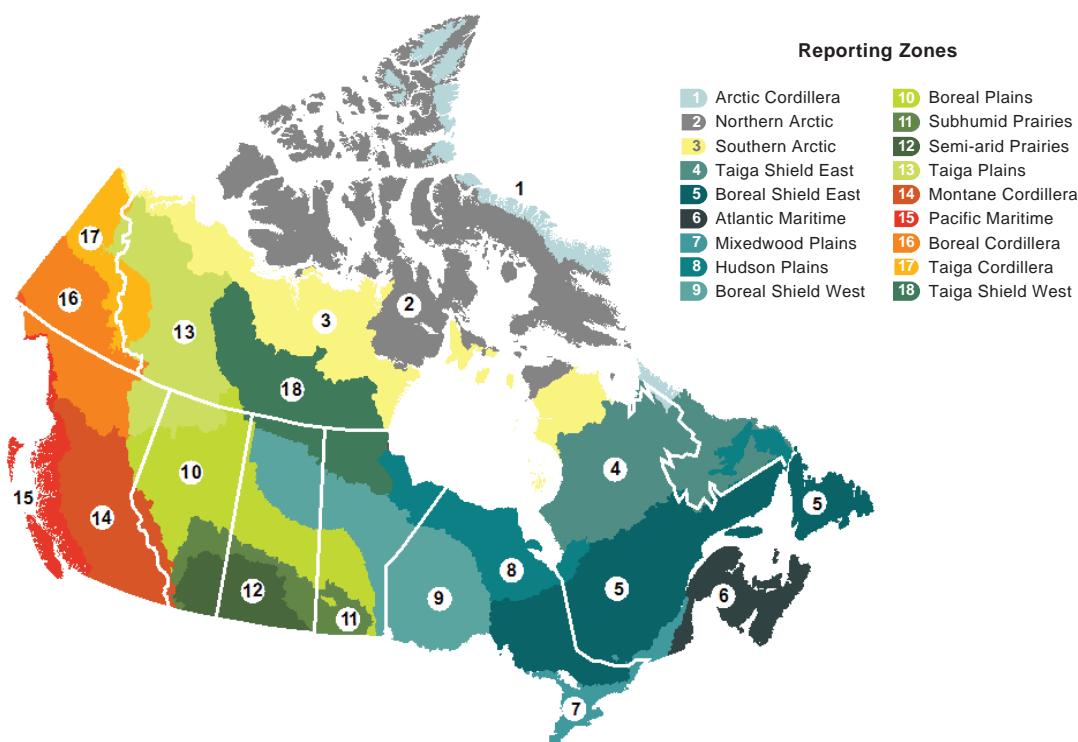
A country-specific model (NFCMARS-HWP) is used to estimate the emissions from the use and disposal of wood products reported under the Harvested Wood Products category. For details on the methods and parameters used in the model, see section A3.5.3.

Emissions due to the conversion and management of peatlands for peat extraction, the creation of flooded lands (reservoirs) on areas with no evidence of forest clearing and from the conversion of grasslands to Settlements, are estimated using IPCC Tier 2 methods and country-specific parameters (see sections A3.5.6.1, A3.5.6.2 and A3.5.7.3). Net CO₂ removals from the growth of urban trees are estimated using an IPCC Tier 2A approach (see section A3.5.7.1). In addition, emissions due to the occasional burning of grassland are estimated using an IPCC Tier 1 method and default emissions factors (see section A3.5.5.1).

A compilation of the spatial framework and parameters used to develop and report the LULUCF estimates is provided in this annex (see Figure A6.5–1 to Figure A6.5–6 and Table A6.5–1 to Table A6.5–9).

A6.5.1. Reporting Zones

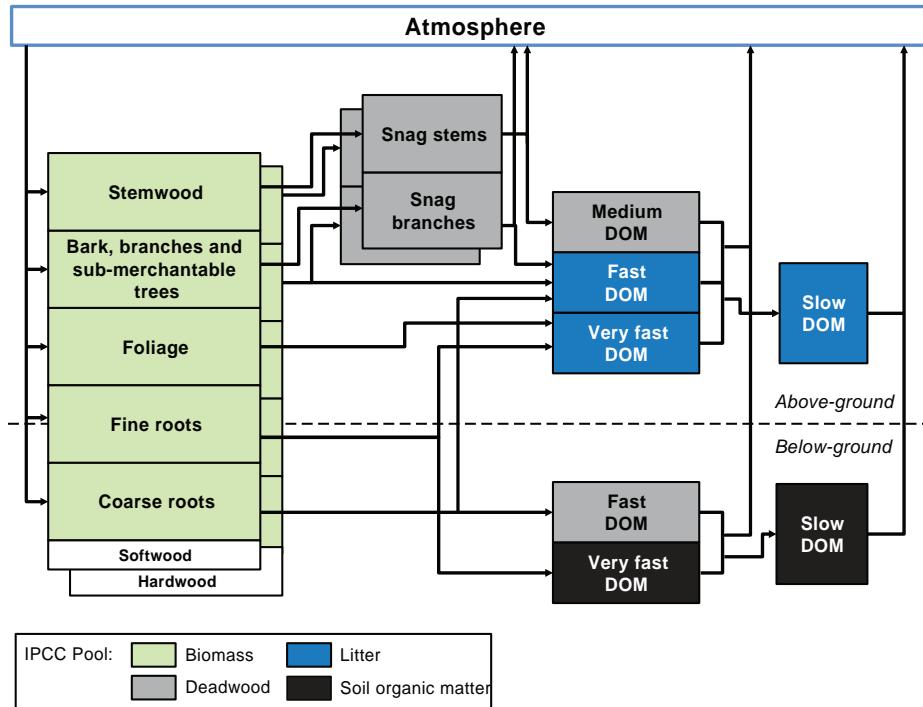
Figure A6.5–1 Reporting Zones for LULUCF estimates



⁴ Available online at: <https://sis.agr.gc.ca/cansis/nsdb/index.html>

A6.5.2. Forest Land

Figure A6.5-2 Carbon Transfers Between Forest Pools



Note: Source = White et al. (2008), updated

Figure A6.5–3 Disturbance Matrix Parameters for Carbon Modelling (Selected Examples)

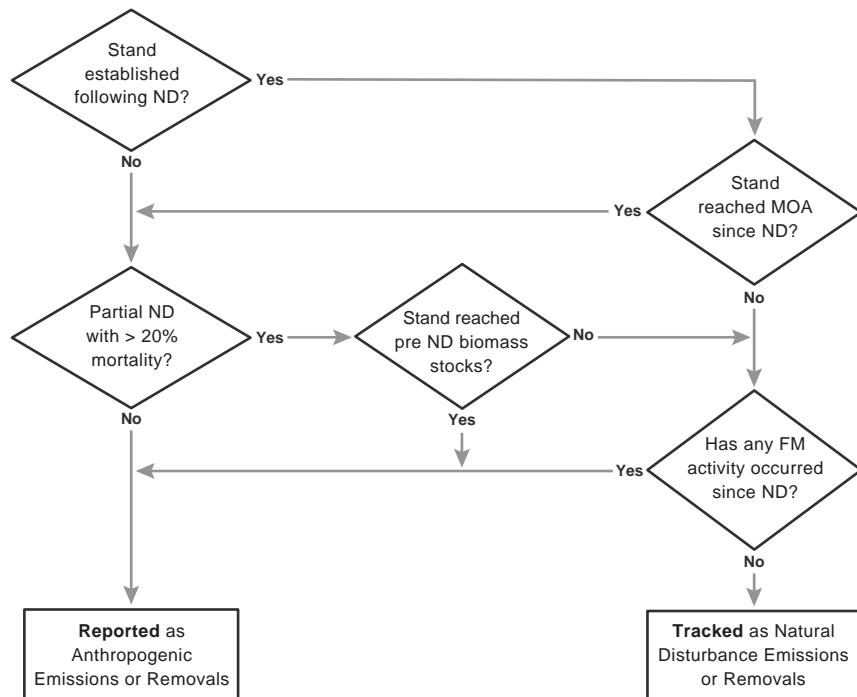
Disturbance Matrix Simulating the Carbon Transfers Associated with Clear-Cut Harvesting and Salvage Logging Applicable in all Ecozones Except Those in Alberta and Quebec

	13	14	15	16	17	18	19	24	25	Products
1.				0.15						0.85
2.	1									
3.		1								
4.		1								
5.		0.5	0.5							
6.	0.5	0.5								
7.				0.15						0.85
8.	1									
9.		1								
10.		1								
11.		0.5	0.5							
12.	0.5	0.5								
13.	1									
14.		1								
15.			1							
16.			1							
17.				1						
18.					1					
19.						1				
20.							0.5			0.5
21.	1									
22.							0.5			0.5
23.		1								
24.								1		
25.									1	

Disturbance Matrix Simulating the Carbon Transfers Associated with Firewood Collection from Hardwood applicable in Atlantic Maritime and Mixewood Plains Ecozones

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Products
1.	1																									
2.		1																								
3.			1																							
4.				1																						
5.					1																					
6.						1																				
7.							0.7																			0.3
8.								0.7																		
9.									0.7																	0.2
10.										0.7																0.3
11.											0.7															
12.												0.7	0.15	0.15												
13.													1													
14.														1												
15.															1											
16.																1										
17.																	1									
18.																		1								
19.																			1							
20.																				1						
21.																					0.5					0.5
22.																						0.5				0.5
23.																							1			
24.																								1		
25.																									1	

Figure A6.5-4 Decision Tree for Managed Forest



Notes:

ND = Natural disturbance
 MOA = Minimum operable age
 FM = Forest management

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A6.5.3. Harvested Wood Products

Table A6.5-1 Default Parameter Values Used in Harvested Wood Products Analysis

Description	Units	Value
Bark expansion factor, Softwoods	dimensionless	1.11 ^a
Bark expansion factor, Hardwoods	dimensionless	1.15 ^a
Bark expansion factor, Mixedwoods	dimensionless	1.13 ^a
C content of wood	tonnes C od tonne ^{-1,b}	0.5 ^c

Note:

a. IPCC (2006) (Vol. 4, Table 12.5)

b. Tonnes carbon per oven dry tonne (od tonne) of wood material.

c. IPCC (2006) (Vol. 4, Table 12.4)

Table A6.5–2 Wood Densities of Commodities

Country/Countries	Description	Units	Value
Canada	Species-weighted average density, Roundwood	od tonne m ⁻³	0.386 ^a
Canada	Species-weighted average density, Sawnwood	od tonne m ⁻³	0.481 ^a
Canada	Species-weighted average density, Other industrial roundwood	od tonne m ⁻³	0.583 ^a
Canada	Species-weighted average density, Panels	od tonne m ⁻³	0.643 ^b
Canada	Species-weighted average density, Bioenergy	od tonne m ⁻³	0.523 ^c
U.S.	Coniferous (C) roundwood	od tonne green m ⁻³	0.455 ^d
U.S.	Nonconiferous (NC) roundwood	od tonne green m ⁻³	0.527 ^d
U.S.	C+NC roundwood	od tonne green m ⁻³	0.465 ^d
U.S.	Hardwood (HW) plywood & veneer	tonnes C m ⁻³	0.28 ^e
U.S.	Softwood (SW) lumber	tonnes C m ⁻³	0.22 ^e
U.S.	HW lumber	tonnes C m ⁻³	0.26 ^e
U.S.	Particle board	tonnes C m ⁻³	0.29 ^e
U.S.	Hardboard	tonnes C m ⁻³	0.42 ^e
U.S.	Medium density fibreboard	tonnes C m ⁻³	0.32 ^e
U.S.	Fibreboard, compressed	tonnes C m ⁻³	0.37 ^a
U.S.	Pulp, paper & board	tonnes C ad tonne ⁻¹	0.42 ^e
U.S.	Insulating board	tonnes C m ⁻³	0.45 ^e
All	Sawnwood – C	od tonne m ⁻³	0.45 ^f
All	Sawnwood – NC	od tonne m ⁻³	0.45 ^f
All	Panels, structural	od tonne m ⁻³	0.628 ^f
All	Panels, non-structural	od tonne m ⁻³	0.628 ^f
All	Paper	od tonne ad tonne ⁻¹	0.9 ^f
All	Wood pulp	od tonne ad tonne ⁻¹	0.9 ^f

Notes:

od tonne = Oven dry tonne of wood material

ad tonne = Air dry tonne of product

a. Country-specific values derived from internal analysis of Canada's forest management levels carried out in 2011-2012

b. Derived from Briggs D (1994)

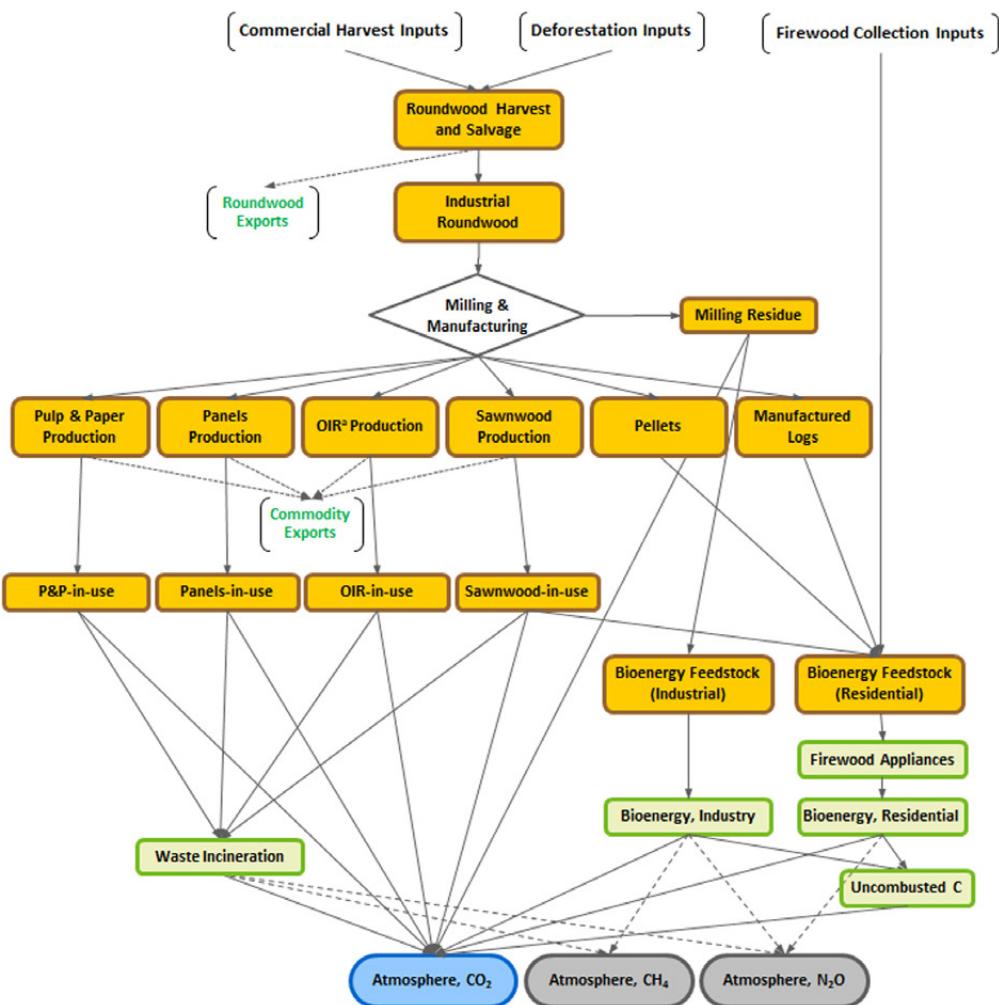
c. Average of the values for roundwood, sawnwood, other industrial roundwood and panels

d. FAO (2010)

e. Skog (2008)

f. IPCC (2006) (Vol. 4, Table 12.4)

Figure A6.5–5 Carbon Flows in Harvested Wood Products



Note:

OIR = Other Industrial Roundwood

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Table A6.5–3 Half-Life Parameters (Years) of Harvested Wood Products In-Use

Country/Countries	Description ^a	Value
Canada	Sawnwood	35 ^b
Canada	Wood panels	25 ^c
Canada	Pulp and paper	2 ^b
Canada	Other industrial roundwood	35 ^b
U.S.	Sawnwood	40 ^b
U.S.	Wood panels	27.04 ^c
U.S.	Pulp and paper	3.25 ^c
U.S.	Other industrial roundwood	40 ^b
Rest of world	Sawnwood	35 ^b
Rest of world	Wood panels	25 ^c
Rest of world	Pulp and paper	2 ^b
Rest of world	Other industrial roundwood	35 ^b

Note:

a. Firewood and mill residue assumed to be burned for the former, or disposed of for the latter, in the year of harvest.

b. IPCC (2003) (Appendix 3a.1, Table 3a.1.3)

c. Derived from IPCC (2003) (Appendix 3a.1, Table 3a.1.3)

A6.5.4. Cropland

Table A6.5-4 Coefficients of Agricultural Area-based Soil Organic Carbon factors by Land Management Change (LMC)

Zone ^{a, e}	LMC ^{b, c}	k yr ⁻¹	ΔC _{LMCmax} (Mg ha ⁻¹)	Final Year of Effect after LMC ^d	Mean Annual Linear Coefficient over Duration of Effect of LMC (Mg ha ⁻¹ yr ⁻¹)	Mean Annual Linear Coefficient over First 20 Years after LMC (Mg ha ⁻¹ yr ⁻¹)
East Atlantic	IT to NT	0.0216	3.5	52	0.05	0.06
	IT to RT	0.0251	2.4	36	0.04	0.05
	RT to NT	0.0233	1.1	1	0.03	0
	Increase perennial	0.0217	43.4	167	0.25	0.77
East Central	IT to NT	0.025	5	65	0.06	0.1
	IT to RT	0.0261	1.9	25	0.04	0.04
	RT to NT	0.0255	3.2	46	0.05	0.06
	Increase perennial	0.0247	38.2	147	0.25	0.74
Parkland	IT to NT	0.0286	6.5	70	0.08	0.14
	IT to RT	0.0242	2.8	41	0.04	0.05
	RT to NT	0.0263	3.7	51	0.05	0.07
	Increase perennial	0.0233	29.4	142	0.2	0.55
Semi-arid Prairies	IT to NT	0.0261	4.9	63	0.06	0.1
	IT to RT	0.0188	2.3	30	0.03	0.04
	RT to NT	0.0222	2.5	37	0.04	0.05
	Increase perennial	0.0281	26.1	120	0.21	0.56
West	IT to NT	0.0122	4.8	69	0.04	0.05
	IT to RT	0.0116	0.8	0	0	0
	RT to NT	0.0119	3.9	53	0.03	0.04
	Increase perennial	0.0155	34.4	198	0.17	0.46

Notes:

Effective Linear Coefficients of SOC were generated using $F_{LMC(t)} = \Delta C_{LMCmax} \times [1 - \exp(-k \times t)]$.

a. Area-weighted summary: East Atlantic is the Atlantic Maritime reporting zone plus the Boreal Shield reporting zone in Newfoundland and Labrador; East Central is the Mixedwood Plains reporting zone plus the Boreal Shield East reporting zone in Ontario and Quebec; Parkland is the Subhumid Prairies, Boreal Shield West and Boreal Plains reporting zones plus those parts of the Montane Cordillera reporting zone with agricultural activity contiguous to agricultural activity within the rest of the Parkland zone; and West is the Pacific Maritime reporting zone plus the Montane Cordillera reporting zone excepting that portion of the latter that is included in the Parkland zone as described above.

b. For LMCs in the opposite direction to that listed, the F_{LMCmax} will be the negative of the value listed.

c. IT = intensive tillage, RT = reduced tillage, NT = no-till

d. No further C changes once the absolute value of the rate of change is less than 25 kg C ha⁻¹ yr⁻¹.

e. Factors estimated from changes to yield, and as a consequence, carbon inputs to soils cannot be summarized by single regional factors, alternative approaches to presenting simplified factors are under development.

Table A6.5-5 Coefficients of Agricultural Soil Organic Carbon by Land Management Change (LMC)

Livestock	Manure Type	C:N Ratio ^a
Dairy Cattle	Liquid	15.0 (± 7.3) ^b
	Solid	13.1 (± 1.4) ^c
Beef Cattle	Solid	14.1 (± 4.7) ^d
Swine	Liquid	10.5 (± 2.4) ^e
Poultry	Solid	5.0 (± 0.4) ^f

Notes:

a. Numbers in the parentheses are standard deviations

b. Bhandral et al. (2009); Rochette et al. (2008); Pelster et al. (2012); Lynch et al. (2005); Maillard et al. (2015); Maillard et al. (2016); Aoyama et al. (1999)

c. Rochette et al. (2008)

d. Hao et al. (2003); Sommerfeldt et al. (1988); Izaurralde et al. (2001); Grant et al. (2001); Pare et al. (1999); Larney and Janzen (1996)

e. Pelster et al. (2012); Chantigny et al. (2000); Chantigny et al. (2007); Chantigny et al. (2010); Chantigny et al. (2012)

f. Pelster et al. (2012); Forge et al. (2016); Rees et al. (2014); Larney and Janzen (1996)

Table A6.5–6 Manure-induced C Retention in Soils under annual crop production from Manure Application

Manure Type	Manure-induced C Retention %
Solid Swine and Cattle Manure	25.6 (± 1.4) ^a
Composted Swine Manure	35.5 (± 2.2)
Liquid Swine and Cattle Manure	4.7 (± 3.6)

Note:

a. Standard errors

Data source = Liang et al. (2021)

A6.5.5. Wetlands

Table A6.5–7 Parameters and Emission Factors (EF) for Estimating Emissions from Peat Extraction

Emission Factor/Parameter	Unit ^a	Value
Biomass Clearing		
Forest land biomass cleared	t C ha ⁻¹	19.2 ^b
Other land biomass cleared	t C ha ⁻¹	2.8 ^b
Drainage		
CO ₂ from drained areas	t CO ₂ ha ⁻¹ yr ⁻¹	11.44 ^c
CO ₂ -DOC from drained areas	t CO ₂ ha ⁻¹ yr ⁻¹	0.60 ^d
CH ₄ from drained fields	t CH ₄ ha ⁻¹ yr ⁻¹	0.008 ^e
CH ₄ from drainage ditches	t CH ₄ ha ⁻¹ yr ⁻¹	0.15 ^f
N ₂ O from drained areas	t N ₂ O ha ⁻¹ yr ⁻¹	0.00047 ^g
CO ₂ from abandoned block-cut areas	t CO ₂ ha ⁻¹ yr ⁻¹	8.6 ^h
CH ₄ from abandoned block-cut areas	t CH ₄ ha ⁻¹ yr ⁻¹	0.012 ⁱ
CO ₂ tree plantation biomass uptake	t CO ₂ ha ⁻¹ yr ⁻¹	-0.32 ^j
Peat Stockpiling and Product Production		
Amount of stockpiled peat	t C ha ⁻¹	50 ^k
Exponential decay constant, stockpiled peat		0.05 ^k
Carbon fraction of peat products	t C t air-dry peat ⁻¹	0.26 ^l
Rewetting and Restoration		
CO ₂ from restored areas	t CO ₂ ha ⁻¹ yr ⁻¹	7.60 ^m
CO ₂ -DOC from restored areas	t CO ₂ ha ⁻¹ yr ⁻¹	0.13 ^d
CH ₄ from restored fields	t CH ₄ ha ⁻¹ yr ⁻¹	0.03 ^e
CH ₄ from restored ditches	t CH ₄ ha ⁻¹ yr ⁻¹	0.28 ⁿ
N ₂ O from restored areas	t N ₂ O ha ⁻¹ yr ⁻¹	N/A ^o

Notes:

- a. All units where the greenhouse gas (GHG) is specified use units of the relevant GHG (CO₂, CH₄ or N₂O) instead of carbon (C) or nitrogen (N).
- b. Hayne and Vericki, 2011
- c. Moore et al., 2002, as cited in Cleary, 2003; Glatzel et al., 2003; Waddington et al., 2010; Strack and Zuback, 2013; Strack et al., 2014
- d. Waddington et al., 2008; Strack and Zuback, 2013
- e. Moore et al., 2002 as cited in Cleary, 2003; Waddington and Day, 2007; Strack and Zuback, 2013; Strack et al., 2014
- f. Waddington and Day, 2007
- g. IPCC, 2014 (Table 2.5, Default value for Boreal & Temperate climate zone)
- h. Waddington and Price, 2000; Waddington and Warner, 2001; Waddington et al., 2002; McNeil and Waddington, 2003
- i. Waddington and Price, 2000
- j. Garcia Bravo, 2015
- k. Cleary, 2003
- l. Hayne et al., 2014
- m. Moore et al., 2002 as cited in Cleary, 2003; Petrone et al., 2001; Petrone et al., 2003; Waddington et al., 2010; Strack and Zuback, 2013; Strack et al., 2014
- n. Waddington and Day, 2007; Strack and Zuback, 2013
- o. IPCC, 2014, Default assumption of no N₂O emissions from rewetted/restored areas

A6.5.6. Settlements

Table A6.5–8 Carbon Storage and Sequestration in Urban Trees

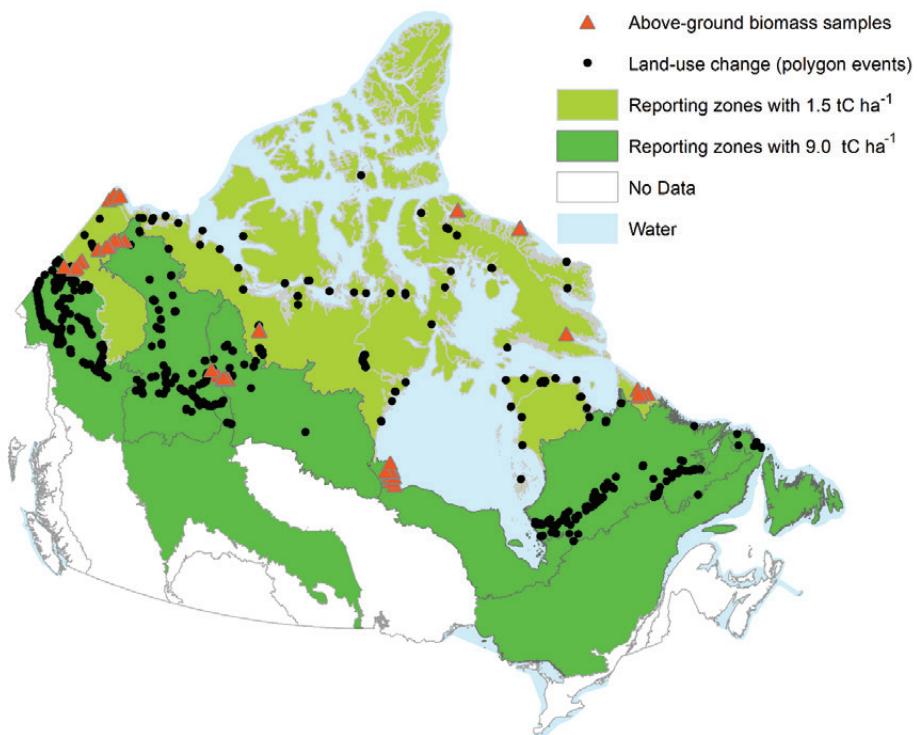
Reconciliation Unit (RU)	Carbon Storage (t C ha ⁻¹)	Carbon Sequestration (t C ha ⁻¹ yr ⁻¹)
1 NL – Boreal Shield East	40	3.0
5 NS – Atlantic Maritime	62	3.4
6 PE – Atlantic Maritime	62	3.4
7 NB – Atlantic Maritime	62	3.4
11 QC – Atlantic Maritime	62	3.4
12 QC – Mixedwood Plains	58	2.4
15 QC – Boreal Shield East	40	3.0
16 ON – Boreal Shield West	40	3.0
17 ON – Mixedwood Plains	58	2.4
19 ON – Boreal Shield East	40	3.0
24 MB – Subhumid Prairies	55	2.9
28 SK – Boreal Plains	40	3.0
30 SK – Semiarid Prairies	55	2.9
34 AB – Boreal Plains	40	3.0
35 AB – Subhumid Prairies	55	2.9
37 AB – Semiarid Prairies	55	2.9
41 BC – Pacific Maritime	97	6.9
42 BC – Montane Cordillera	23	1.4

Note:

Source = Steenberg et al., 2021

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Figure A6.5–6 Map of Sample Points and Land-Use Change Events in Canada's North



Note: More southerly reporting zones are attributed to the 9 tC ha⁻¹ biomass class, as some sites border on the northernmost boundary of these reporting zones.

A6.5.7. Forest Conversion

Table A6.5–9 Soil Organic Carbon in Forest and Agricultural Land (0- to 30-cm soil depth)

Soil Texture	Soil Organic Carbon (Mg C ha^{-1})		Difference (%)
	Forested Land ^a	Cropland ^a	
Eastern Canada			
Coarse	85 (26)	68 (42)	-20
Medium	99 (38)	77 (35)	-22
Fine	99 (58)	78 (36)	-21
Western Canada			
Coarse	73 (39)	74 (38)	0
Medium	66 (30)	73 (30)	4
Fine	74 (38)	77 (25)	1

Note:
a. Standard deviation in parentheses.

A6.6. Biomass Combustion

A6.6.1. CO₂

Emissions of CO₂ from the combustion of biomass originated from forests or other woodlands (whether for energy use, from prescribed burning or from wildfires) are not included in National Inventory totals. Emissions from prescribed burning and from the combustion of this biomass for energy use are estimated and reported in the Land Use, Land-use Change and Forestry (LULUCF) sector, in common reporting format (CRF) Tables 4(V) and 4.G respectively. Forest wildfires are considered uncontrollable natural disturbances in the modelling and reporting approach used in the LULUCF sector by which these emissions and subsequent removals are estimated and tracked separately from emissions/removals resulting from commercially managed forest stands, more details on his approach can be found in Annex A3.5.2.4.

The emissions related to the combustion of biomass for energy use are reported as memo items in the CRF tables of the Energy sector, as required by the United Nations Framework Convention on Climate Change (UNFCCC).

Emissions from industrial combustion of biomass are dependent primarily on the characteristics of the fuel being combusted. The CO₂ emission factor (Table A6.6–1) for industrial wood waste has been developed from facility source sampling data collected by the U.S. EPA in units of lb/MMBTU (one million British thermal units; U.S. EPA, 2003). The U.S. EPA data were converted to kg/tonne at 0% moisture content (m.c.) using a higher heating value (HHV) of 20.44 MJ/kg, which was developed from an internal review of available moisture content and heating value data. The emission factor for spent pulping liquor is calculated from data collected by the National Council for Air and Stream Improvement (NCASI), based on carbon content assuming a 1% correction for unoxidized carbon (NCASI, 2010). The NCASI emission factors were reported in units of kg/GJ HHV, which was converted to kg/tonne at 0% m.c. using a HHV of 13.7 MJ/kg (Tran, 2014).

CO₂ emission factor for residential combustion (Table A6.6–1) is based on the default 2006 IPCC guidelines. The IPCC data were converted to g/kg at 19% moisture content using a lower heating value (LHV) of 13.2 MJ/kg, which was calculated based on the assumption that LHV is 20% less than the HHV (FPL, 2004). The HHV was developed from an internal review of available moisture content and heating value data.

CO₂ emissions occur during forest wildfires and from controlled burning during forest conversion activities. The carbon emitted as CO₂ (CO₂-C) during forest fires is considered in the forest carbon balance, whereas the CO₂-C emitted during controlled burns is reported under the new land-use categories. There is no unique CO₂ emission factor applicable to all fires, as the proportion of CO₂-C emitted for each pool can be specific to the pool, the type of forest and disturbance, and the ecological zone (see section A3.5).

Table A6.6–1 Emission Factors for Biomass

Source ^a	Description	Emission Factor (g/kg fuel)		
		CO ₂	CH ₄	N ₂ O
Wood Fuel / Wood Waste	Industrial Combustion	1 715 ^b	0.1 ^c	0.07 ^c
Forest Wildfires	Open Combustion	NA	NA ^d	NA ^e
Controlled Burning	Open Combustion	NA	NA ^d	NA ^e
Spent Pulping Liquor	Industrial Combustion	1 250 ^f	0.03 ^g	0.005 ^g
Stoves and Fireplaces	Residential Combustion			
Conventional Stoves		1 539 ^h	12.9 ^h	0.12 ^h
Conventional Fireplaces and Inserts		1 539 ^h	12.9 ^h	0.12 ^h
Stoves/Fireplaces with Advanced Technology or Catalytic Control		1 539 ^h	5.9 ^h	0.12 ^h
Pellet Stove		1 652 ^b	4.12 ^h	0.059 ^h
Other Wood-burning Equipment		1 539 ^h	4.12 ^h	0.059 ^h

Notes:

NA = Not applicable

a. CO₂ emissions from biomass combusted for energy or agricultural purposes are not included in inventory totals, whereas CH₄ and N₂O emissions from these sources are inventoried under the Energy Sector. All greenhouse gas (GHG) emissions, including CO₂ emissions from biomass burned in managed forests (wildfires and controlled burning), are reported under Land-Use, Land-use Change and Forestry (LULUCF) and excluded from national inventory totals.

b. Adapted from U.S. EPA (2003).

c. Adapted from U.S. EPA (2003) and NCASI TB₉₉₈ (2012).

d. Emission ratio for CH₄ is 1/90th CO₂. See NIR Annex 3.4.

e. Emission ratio for N₂O is 0.017% CO₂. See NIR Annex 3.4.

f. Adapted from NCASI (2011).

g. Adapted from NCASI (2012).

h. Adapted from IPCC (2006).

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A6.6.2. CH₄

Emissions of CH₄ from residential combustion of firewood are technology-dependent. The CH₄ emission factors are based on the default 2006 IPCC guidelines. The IPCC values were converted to g/kg at 19% m.c. using the same method used for the CO₂ conversion.

Emissions from industrial combustion of biomass are dependent primarily on the characteristics of the fuel being combusted. The emission factor (Table A6.6–1) for CH₄ from industrial wood waste has been developed from facility source sampling data collected by the U.S. EPA in units of lb/MMBTU (U.S. EPA, 2003) and collected by the NCASI in units of kg/MMBTU and converted to kg/tonne at 0% m.c. as discussed in section A6.6.1. The emission factor for CH₄ from spent pulping liquor has been developed using source sampling data from NCASI in units of kg/MMBTU, converted to kg/tonne at 0% m.c. using a HHV of 13.7 MJ/kg as discussed in section A6.6.1.

Emission factors from landfill gas (Table A6.6–2) are adapted from the IPCC (2006).

Emissions of carbon as CH₄ (CH₄-C) from wildfires and controlled burning are always equal to 1/90th of CO₂-C emissions.

A6.6.3. N₂O

Emissions of N₂O from residential combustion of firewood are technology-dependent. The N₂O emission factors are based on the default 2006 IPCC guidelines. The IPCC values were converted to g/kg at 19% m.c. using the same method used for the CO₂ conversion.

Emissions from industrial combustion of biomass are dependent primarily on the characteristics of the fuel being combusted. Emission factors (Table A6.6–1) for industrial wood waste has been developed from facility source sampling data collected by the U.S. EPA in units of lb/MMBTU (U.S. EPA, 2003) and collected by the National Council for Air and Stream Improvements (NCASI) in units of kg/MMBTU and converted to kg/tonne at 0% m.c. as discussed in section A6.6.1. The emission factor for N₂O from spent pulping liquor has been developed using source sampling data from NCASI in units of kg/MMBTU, converted to kg/tonne at 0% m.c. using a HHV of 13.7 MJ/kg as discussed in section A6.6.1.

Emission factors for landfill gas (Table A6.6–2) are adapted from the IPCC (2006).

N₂O emissions from wildfires and controlled burning are equal to 0.017% vol/vol of CO₂ emissions. Since both gases have the same molecular weight, the same ratio can be applied on a mass basis (see section A3.5.2).

Table A6.6–2 Emission Factors for Landfill Gas Combustion

Source	Description	Emission Factor			Emissin Factor Units
		CO ₂	CH ₄	N ₂ O	
Landfill Gas	Industrial Combustion (for Energy)	2 752 ^a	0,05 ^a	0,05 ^a	kg/t CH ₄ Utilized for Energy
Landfill Gas	Flaring	NE	30 ^b	NE	kg/t CH ₄ Flared

Notes:
 NE = Not estimated
 a. Adapted from IPCC (2006) (Vol. 2, Table 2.2)
 b. U.S. EPA (1995)

A6.7. Waste

A6.7.1. Municipal Wastewater Treatment and Discharge

A6.7.1.1. CH₄

Emissions from municipal wastewater treatment and discharge are dependent on the organic loading of the effluent stream (which is a function of population), and the type of wastewater treatment provided. Emission factors (EF) are the product of the methane correction factor (MCF), which is the technology-specific estimate of the fraction of biological oxygen demand (BOD) that will ultimately degrade anaerobically, and the maximum methane producing capacity (B_0), which is expressed in terms of kg CH₄/kg BOD removed. The IPCC default value of 0.6 kg CH₄/kg BOD for B_0 was not used. The AECOM (2011) study commissioned by Environment Canada confirmed that its derivation from the 0.25 kg CH₄/kg COD was erroneous, where COD is the chemical oxygen demand. A Canada specific value of 0.36 CH₄/kg BOD for B_0 was used (AECOM, 2011).

The MCF and EF values for CH₄ emissions from wastewater treatment and discharge, by treatment technology are shown in Table A6.7–1.

Table A6.7–1 Methane Correction Factors (MCF) and Emission Factors (EF) for CH₄ from Wastewater Treatment and Discharge

Treatment	MCF	EF
No Treatment	0.1 ^a	0.036
Primary	0.018 ^b	0.0036
Aerobic Lagoon	0 ^a	0
Anaerobic Lagoon	0.8 ^a	0.288
Facultative Lagoon	0.2 ^a	0.072
Other / Unspecified Lagoon	0.2 ^c	0.072
Secondary Anaerobic	0.8 ^a	0.288
Secondary Activated Sludge	0.01 ^b	0.0036
Trickling Filter	0.01 ^b	0.0036
Trickling Filter – High Rate	0.01 ^b	0.0036
Rotating Biological Contactor	0.01 ^b	0.0036
Sequencing Batch Reactor	0.05 ^d	0.018
Secondary Biofiltration	0.01 ^b	0.0036
Secondary with Biological Nutrient Removal	0.01 ^b	0.0036
Septic	0.5 ^a	0.18
Septic with Marine Outfall	0.5 ^a	0.18
Wetland	0.17 ^e	0.0612
Other / Unknown	0.2 ^f	0.072

Notes:

EF calculated as MCF x B_0 , where B_0 is Canada-specific value of 0.36

a. IPCC (2006) (Vol. 5, Chapter 6, Table 6.3)

b. IPCC (2019) Guideline Refinement

c. Assuming Unspecified lagoon types were assumed to be facultative lagoons.

d. Taseli (2018). Point source pollution and climate change impact from Sequential Batch Reactor wastewater treatment plant.

e. IPCC Supplement to 2006 Guidelines for Wetlands (2014). Chapter 6. Mean value of MCF's for three wetland types provided in document.

f. Assuming facilities of unknown or other treatment type are either facultative lagoon or untreated discharge to sea. The median value of the MCF and EF of these technologies used.

A6.7.1.2. N₂O

N₂O emissions from wastewater are a function of the nitrogen entering the wastewater stream, which is, in turn a function of protein consumption per capita, population, nitrogen content in protein, and adjustment factors for input of non-consumed nitrogen (e.g. from washing) and industrial inputs. The emission factor used is the IPCC 2006 Guideline default value of 0.005 kg N₂O-N/kg N (IPCC, 2006). The emission factor for N₂O from wastewater treatment and discharge is shown in Table A6.7–2.

Table A6.7–2 Emission Factors for N₂O from Wastewater Treatment and Discharge

Treatment Category	EF (kg N ₂ O-N/kg N)	Units
No Treatment	0 ^a	kg N ₂ O-N/kg N ^d
Primary	0 ^b	
Aerobic Lagoon	0 ^b	
Anaerobic Lagoon	0 ^a	
Facultative Lagoon	0 ^b	
Other / Unspecified Lagoon	0 ^c	
Secondary Anaerobic	0 ^a	
Secondary Activated Sludge	0.016 ^a	
Trickling Filter	0.016 ^a	
Trickling Filter – High Rate	0.016 ^a	
Rotating Biological Contactor	0.016 ^a	
Sequencing Batch Reactor	0.016 ^a	
Secondary Biofiltration	0.016 ^b	
Secondary with Biological Nutrient Removal	0.016 ^a	
Septic	0.0045 ^a	
Septic with Marine Outfall	0 ^a	
Wetland	0 ^b	
Other / Unknown	0.016 ^c	

Notes:

- a. IPCC (2019) Guideline Refinement
- b. ECCC Estimate
- c. Modelled as facultative lagoon
- d. To convert N₂O-N to N₂O, multiply by 44/28

A6.7.2. Waste Incineration

The emission factors for CO₂, CH₄, and N₂O for waste incineration are shown in Table A6.7–3.

Table A6.7–3 Emission Factors for Waste Incineration

Category	Emission Factors			Units
	CO ₂	CH ₄	N ₂ O	
Municipal Solid Waste Incineration – Continuous – Fluidized Bed	3 666.67*	0.0002	0.00005	kg / tonne waste (for CH ₄ , N ₂ O) *kg CO ₂ / tonne fossil C in waste
Municipal Solid Waste Incineration – Continuous – Stoker		0	0.00005	
Municipal Solid Waste Incineration – Semi-Continuous – Fluidized Bed		0.006	0.00005	
Municipal Solid Waste Incineration – Semi-Continuous – Stoker		0.188	0.00005	
Municipal Solid Waste Incineration – Batch – Fluidized Bed		0.06	0.00006	
Municipal Solid Waste Incineration – Batch – Stoker		0.237	0.00006	
Sewage Sludge Incineration	1 650.00	9.70	0.99	kg / tonne sewage sludge
Hazardous Waste Incineration	1 650.00	0.17	3.16	kg / tonne waste
Clinical Waste Incineration – Continuous	572.00	0.0002	0.05	kg / tonne waste
Clinical Waste Incineration – Batch		0.06	0.06	kg / tonne waste
Industrial Sludge – Continuous	1 650.00	0.0002	0.45	kg / tonne waste
Industrial Sludge – Batch		0.06	0.45	kg / tonne waste
Fossil Liquid Waste – Continuous		0.0002	0.1	kg / tonne waste
Fossil Liquid Waste – Batch	2 933.33	0.06	0.1	kg / tonne waste
Fossil Liquid Waste – Semi-Continuous		0.0301	0.1	kg / tonne waste
Industrial – Continuous – Stoker	1 650.00	0.0002	0.05	kg / tonne waste
Industrial – Continuous – Fluidized Bed		0	0.05	kg / tonne waste
Industrial – Semi-Continuous – Fluidized Bed		0.006	0.05	kg / tonne waste
Industrial – Semi-Continuous – Stoker		0.188	0.05	kg / tonne waste
Industrial – Batch – Fluidized Bed		0.06	0.06	kg / tonne waste
Industrial – Batch – Stoker		0.237	0.06	kg / tonne waste

Note: Source – IPCC (2006)

A6.7.2.1. Sewage Sludge Incinerators

Emissions from sewage sludge incinerators are estimated from an emission factor obtained from the IPCC 2006 Guidelines (IPCC, 2006).

A6.7.2.2. Municipal Solid Waste Incinerators

The emission estimates from municipal solid waste incineration are calculated based on batch or continuous operations, and based on stoker or fluidized bed combustion technology. The emission factors used are from the IPCC 2006 Guidelines (IPCC, 2006). For CO₂ emissions, only the non-biogenic (fossil) portion of the waste is included when calculating emissions.

A6.7.2.3. Hazardous Waste Incinerators

The CO₂ emission factors for hazardous waste incineration are taken from the IPCC 2006 Guidelines (IPCC, 2006). The CO₂ emission factor is based on a carbon content of 50% and fossil carbon content of 90% of the carbon content. CH₄ and N₂O emission factors were developed for Canada using emissions from a facility.

A6.7.2.4. Clinical Waste Incinerators

The emission factors for clinical waste incineration are taken from the IPCC 2006 Guidelines (IPCC, 2006). The CO₂ emission factor is based on a carbon content of 45%.

A6.7.3. Biological Treatment of Solid Waste

The emission factors for CO₂, CH₄, and N₂O for the biological treatment of solid waste are shown in Table A6.7–4.

Table A6.7–4 Emission Factors for the Biological Treatment of Solid Waste

Category	Waste of Facility Type	Emission Factors			Units
		CO ₂	CH ₄	N ₂ O	
Anaerobic Digestion	Off-farm facilities ^a	NA	2.10	NA	% of methane produced in biogas
Composting	Yard Waste ^b	NA	1.72	0.25	g/kg Wet Waste
	Biosolids or Manure ^b	NA	3.54	0.18	g/kg Wet Waste
	Mixture of Wastes ^b	NA	1.09	0.11	g/kg Wet Waste
	Municipal Solid Waste ^b	NA	1.51	0.18	g/kg Wet Waste

Notes:

NA = Not applicable

a. ECCC(2020b)

b. ECCC(2020c)

ANNEX 7

OZONE AND AEROSOL PRECURSORS

The Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (FCCC/CP/2013/10/Add.3—UNFCCC 2014) recommends that Parties provide information on indirect greenhouse gases (GHGs) such as carbon monoxide (CO), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC) and sulphur oxides (SO_x) in the National Inventory Report (NIR).

Aerosols are liquid, solid or mixed particles suspended in the atmosphere. Aerosol particles are either emitted directly to the atmosphere or produced in the atmosphere from precursor gases. While these gases do not have a direct global warming effect, they either influence the creation and destruction of tropospheric and stratospheric ozone or affect terrestrial radiation absorption, as in the case of SO_x. These gases can impact the climate by acting as short-lived GHGs, alter atmospheric lifetimes of other GHG and quickly react to form GHGs, as in the case of CO reacting with a hydroxyl radical (OH), an oxidation reaction, to form carbon dioxide (CO₂) in the atmosphere—hence the label “indirect GHG.” Emissions from these precursors are produced by a number of sources, such as fossil fuel combustion in the energy and transportation sectors, industrial production and biomass combustion.

Information on ozone and aerosol precursor emissions in Canada, including CO, NO_x, NMVOC and SO_x, is available in Canada’s Air Pollutant Emissions Inventory Report.¹

Canada also reports “indirect CO₂ emissions” that result from the atmospheric oxidation of CO emitted from biomass burned on site after forest harvest and from forest conversion activities. These emissions are reported in the Land Use, Land-use Change, and Forestry (LULUCF) sector within Table 6 of the Common Reporting Format² (CRF). National totals are presented in CRF Tables 10 and Summary 2 with and without these “indirect CO₂ emissions” in accordance with paragraph 29 of the UNFCCC Annex I inventory reporting guidelines (UNFCCC, 2014). Details on the source of these emissions can be found in Chapter 6 and Annex 3.5 of this report.

¹ Canada’s Air Pollutant Emissions Inventory Report can be found at www.canada.ca/APEI.

² Canada’s 2022 Common Reporting Format Tables can be found at <https://unfccc.int/ghg-inventories-annex-i-parties/2022>.

REFERENCES

Annex 1, Key Categories

[IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at <https://www.ipcc-nccc.iges.or.jp/public/2006gl/index.html>.

Annex 2, Uncertainty

[IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at <http://www.ipcc-nccc.iges.or.jp/public/2006gl/index.html>.

Laferrière R, Leblanc-Power G, Tobin S, Tracey K. 2020. *Inventory Emissions Uncertainty for Canada: Accounting for Correlation and Asymmetry with Monte Carlo Simulations*. Unpublished report. Gatineau (QC): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.

Annex 3.1, Methodology and Data for Estimating Emissions from Fossil Fuel Combustion

[AMS] Aircraft Movement Statistics. 2020. Database extracts from Statistics Canada for years 1996 to 2019; Transport Canada personnel for years 1990 to Oct 31, 1996. Ottawa (ON): Statistics Canada.

Alemdag IS. 1984. *Wood density variation of 28 tree species from Ontario*. Petawawa National Forestry Institute. Agriculture Canada. Canadian Forestry Service. Report PI-X-45. 12 pp.

[BADA] Base of Aircraft Data. 2019. Version 3.15. France. Eurocontrol Experimental Centre. Available online at: www.eurocontrol.int.

Canadian Facts. 1997. *Residential fuelwood combustion in Canada*. Canadian Facts. Prepared for the National Emission Inventory and Project Task Group. Toronto (ON): CF Group Inc.

[CEEDC] Canadian Energy and Emissions Data Centre. No date. Database on energy, production and intensity indicators for Canadian industry [accessed 2020 Nov 17]. NAICS 2122 Metal Ore Mining and NAICS 2123 Non-metallic Mineral Mining and Quarrying. Available online at: <https://cieedacdb.rem.sfu.ca/naics-database-download/>.

[CEEDC] Canadian Energy and Emissions Data Centre. No date. Database on energy, production and intensity indicators for Canadian industry [accessed 2019 Dec 23]. NAICS 327310 Cement Manufacturing. Available online at: <https://cieedacdb.rem.sfu.ca/>.

Cheminfo Services Inc., and Clearstone Engineering Ltd. 2014. *Compilation of a national inventory of greenhouse gas and fugitive VOC emissions by the Canadian coal mining industry*. Final report submitted to the Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.

DesRosiers. *Canadian Vehicles in Operation Census (CVIOC) (1989–2015)* prepared by DesRosiers Automotive Consultants.

[ECCC] Environment and Climate Change Canada. 2017a. *Updated coal emission, energy conversion and oxidation factors*. Unpublished Environment Canada internal report. Ottawa (ON): Pollutant Inventories and Reporting Division.

[ECCC] Environment and Climate Change Canada. 2017b. *Updated CO₂ emission factors for gasoline and diesel fuel*. Unpublished report. Prepared by Tobin S., Pollutant Inventories and Reporting Division, Environment and Climate Change Canada. Gatineau (QC).

[ECCC] Environment and Climate Change Canada. 2018a. *Off-road equipment analysis – oil sands mining equipment*. Unpublished report. Prepared by Greenlaw B., Pollutant Inventories and Reporting Division, Environment and Climate Change Canada. Gatineau (QC).

[ECCC] Environment and Climate Change Canada. 2018b. *Off-road equipment analysis – snowmobiles*. Unpublished report. Prepared by B. Greenlaw, Pollutant Inventories and Reporting Division, Environment and Climate Change Canada. Gatineau (QC).

[ECCC] Environment and Climate Change Canada. 2019. *Updated carbon dioxide emission factors for coal combustion*. Unpublished report. Prepared by Kay J., Pollutant Inventories and Reporting Division, Environment and Climate Change Canada. Gatineau (QC).

[ECCC] Environment and Climate Change Canada. 2020. *Rsidential fuelwood consumption in Canada*. Unpublished report. Prepared by Kay J., Pollutant Inventories and Reporting Division, Environment and Climate Change Canada. Gatineau (QC).

[FAA] Federal Aviation Administration. 2018. Air Traffic Organization Policy - Aircraft Type Designators. Order JO 7360.1D. U.S. Department of Transportation.

[FAA] Federal Aviation Administration. 2020. FAA Airports. Available online at: http://www.faa.gov/airports/airport_safety/airportdata_5010/.

Fleming G. 2008a. Canada OD Pairs grt10flts.xls. Federal Aviation Administration.

Fleming G. 2008b. SAGE Airport Codes and Locations. Federal Aviation Administration.

- Fleming G. 2008c. CAEP8 Goals Operations Round 1. Modelling and Database Task Force.
- [FOCA] Federal Office of Civil Aviation. 2007. *Aircraft piston engine emissions summary report*. Swiss Confederation: Federal Department of the Environment, Transport, Energy and Communications. 13 June 2007. Catalogue No. 0/3/33/33-05-003.022.
- Gonzalez JS. 1990. *Wood density of Canadian tree species*. Forestry Canada, Northwest Region. Northern Forestry Centre. Edmonton, AB. Information Report NOR-X-315. 130 pp.
- Hagstrom M. 2010. TPengs FOI orig comp data 031105 corr 071129 Jason Hickey 13 June 2010. Stockholm (SE): Department of Systems Technology, Swedish Defence Research Agency.
- [IATA] International Air Transport Association. 2020. Airline and Location Code Search. Available online at: <https://www.iata.org/en/publications/directories/code-search/>.
- [ICAO] International Civil Aviation Organization. 2016. DOC 8643 – Aircraft Type Designators.
- [ICAO] International Civil Aviation Organization. 2019. ICAO Engine Emissions Databank. Version 26B. Civil Aviation Authority. Available online at: <http://easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank>.
- [ICAO] International Civil Aviation Organization. 2020. ICAO Aircraft Type Designators. Available online at: <https://www.icao.int/publications/doc8643/pages/search.aspx>.
- [IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC guidelines for national greenhouse gas inventories*. Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. Kanagawa (JP): Institute for Global Environmental Studies. Available online at: <http://www.ipcc-nccc.iges.or.jp/public/2006gl/index.html>.
- Jessome AP. 2000. *Strength and related properties of woods grown in Canada*. Forintek Canada Corp. Publication SP-114E. 37 pp.
- McCann TJ. 2000. *1998 fossil fuel and derivative factors*. Prepared by TJ McCann and Associates Ltd. and Clearstone Engineering Ltd. for Environment Canada.
- NAV Canada. 2009. *Canada flight supplement*. Ottawa (ON): NAV Canada.
- NAV Canada. 2018a. *Airport IATA and ICAO codes*. Ottawa (ON): NAV Canada.
- NAV Canada. 2018b. *Canada water aerodrome supplement – Effective 29 March 2019 to 25 April 2019*. Ottawa (ON): NAV Canada.
- NAV Canada. 2019a. *Canada flight supplement – Effective 15 August 2019 to 10 October 2019*. Ottawa (ON): NAV Canada.
- NAV Canada. 2019b. *Canada water aerodrome supplement – Effective 25 April 2019 to 26 March 2020*. Ottawa (ON): NAV Canada.
- Polk RL. 2013. Vehicles in operation (VIO) database. Compiled by R.L. Polk and Co., Southfield (MI).
- Statistics Canada. (No date[a]). *Annual industrial consumption of energy survey*. Tables 25-10-0024-01 and 25-10-0025-01. Available online at: https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5047&Item_Id=44545&lang=en%20.
- Statistics Canada. (No date[b]). *Electric power thermal generating station fuel consumption survey*. Table 25-10-0017-01. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=2196>.
- Statistics Canada. *CANSIM database table 405-0001: Road motor vehicle, trailer and snowmobile registration, terminated, (2000–2013)*. Available online at: <http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=4050001>.
- Statistics Canada. *Canadian vehicle survey (CVS)*. (2000–2009). Catalogue No.53-223-XIE. Available online at : <https://www150.statcan.gc.ca/n1/en/catalogue/53-223-X>.
- Statistics Canada. 1990-. *Report on energy supply and demand in Canada*. Catalogue No. 57-003-X. Available online at: <http://www5.statcan.gc.ca/olc-cel/olc?ObjId=57-003-X&ObjType=2&lang=en&limit=0>.
- Statistics Canada. 1997. *Survey on household energy use*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=7737>.
- Statistics Canada. 2003. *Survey on household energy use*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=22916>.
- Statistics Canada. 2007. *Households and the environment survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=44902>.
- Statistics Canada. 2015. *Households and the environment survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=247867>.
- Statistics Canada. 2017. *Households and the environment survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=433427>.
- Statistics Canada. 2019. *Households and the environment survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=1255380>.
- Stewart Brown Associates. 2013. *Kilometre accumulation rates in British Columbia and Ontario*. Prepared for Environment Canada.
- [TNS] TNS Canadian Facts. 2006. *Residential fuelwood combustion in Canada*. Presented to Environment Canada. Report C1077/BT. Toronto (ON): TNS Global.
- [TNS] TNS Canada. 2012. *Residential fuelwood combustion in Canada*. Presented to Natural Resources Canada. Report 1381/BT. Toronto (ON): TNS Canada.
- [U.S. EPA] United States Environmental Protection Agency. 2017. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2015*. Washington (DC): U.S. Environmental Protection Agency.

- [U.S. EPA] United States Environmental Protection Agency. 2021. *MOVES Versions in Limited Current Use*. Washington (DC): United States Environmental Protection Agency. Available online at: <https://www.epa.gov/moves/moves-versions-limited-current-use>.
- [WBCSD] World Business Council for Sustainable Development. 2005. *CO₂ emissions inventory protocol*. Version 2.0. Cement Sustainability Initiative.
- Wiesen P, Kleffmann J, Kurtenbach R, Becker KH. 1994. Nitrous oxide and methane emissions from aero engines. *Geophysical Research Letters*, 21(18): 2027–2030.
- World Airport Codes. 2020. World Airport Codes Online Database. Available online at: <https://www.world-airport-codes.com/>.

Annex 3.2, Methodology for Fugitive Emissions from Fossil Fuel Production, Processing, Transmission and Distribution

- [AB] Government of Alberta. 2018. *Methane Emission Reduction Regulation*. A.R. 244/2018. 2018 Dec 12 https://open.alberta.ca/dataset/2018_244
- Advisian Ltd. 2019. *Oil and gas inventory information enhancement and economic analysis study: Field data gather and interpret report*. Prepared for Saskatchewan Ministry of Energy and Resources. Calgary (AB).
- [AER] Alberta Energy Regulator. 2020a. *Upstream petroleum industry flaring and venting report*. Available online at: <https://www.aer.ca/documents/sts/ST60B-2019.pdf>.
- [AER] Alberta Energy Regulator. 2020b. *ST50A: Gas processing plants in Alberta* [accessed 2020 Jun 30]. Available online at: <https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st50.html>.
- [AER] Alberta Energy Regulator. 2020c. *Directive 017: Measurement requirements for oil and gas operations*. Available online at: <https://www.aer.ca/regulating-development/rules-and-directives/directives/directive-017>
- [AER] Alberta Energy Regulator. 2021a. *Alberta Energy Resource Industries Monthly Statistics, Gas Supply and Disposition* [revised 2021 Apr 15; accessed 2021 Oct 14]. Available online at: <https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st3>.
- [AER] Alberta Energy Regulator. 2021b. *Alberta's energy reserves and supply/demand outlook* [revised 2021 May; accessed 2021 Oct 26]. Available online at: <https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st98>.
- [AER] Alberta Energy Regulator. 2021c. *AER compliance dashboard – Incidents* [accessed 2021 Oct 15]. Available online at: <http://www1.aer.ca/compliancedashboard/incidents.html>.
- [AER] Alberta Energy Regulator. 2021d. *Well vent flow/gas migration report* [accessed 2021 Aug 16]. Available online at: <https://www1.aer.ca/productcatalogue/365.html>
- [AER] Alberta Energy Regulator. 2021e. *Well infrastructure report (Petrinex)* [accessed 2021 Aug 16]. Available online at: <https://www1.aer.ca/productcatalogue/219.html>
- [AER] Alberta Energy Regulator. 2021f. *Alberta mineable oil sands plant statistics, monthly supplement, December 2020* [revised 2021 Mar 23; accessed 2021 Oct 14]. Available online at: <https://www.aer.ca/documents/sts/ST39-2020.pdf>.
- [AER] Alberta Energy Regulator. 2021g. *ST37: List of wells in Alberta* [accessed 2021 Oct 19]. Available online at: <https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st37>.
- [API] American Petroleum Institute. 2017. Using the Greenhouse Gas Reporting Program (GHGRP) data to improve the National Greenhouse Gas Emissions Inventory for Petroleum and Natural Gas Systems.
- [BC] British Columbia Government. 2019. *Production and distribution of natural gas in BC* [accessed 2019 Jul 5]. Available online at: <https://www2.gov.bc.ca/gov/content/industry/natural-gas-oil/statistics>.
- [BC] British Columbia Government. 2020. *B.C. Gas plant/dehydrator report* [accessed 22 Jul 2020]. Available online at: <https://www2.gov.bc.ca/gov/content/industry/natural-gas-oil/statistics>.
- [BC] British Columbia Government. 2021. *Oil and Gas Activities Act - Drilling and Production Regulation*. B.C. Reg. 282/2010. [Amended 2021 Mar 4]. https://www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/282_2010
- [BCOGC] British Columbia Oil and Gas Commission. 2018. *BC historical facility report*. Provided by BCOGC to Environment and Climate Change Canada [2018 Oct 23].
- [BCOGC] British Columbia Oil and Gas Commission. 2019. *Air summary report*.
- [BCOGC] British Columbia Oil and Gas Commission. 2021a. *Drilling kicks and blowouts by area* [accessed 2021 Oct 5]. Available online at: https://iris.bcogc.ca/generic_ogc/Ext_Accnt.Logon.
- [BCOGC] British Columbia Oil and Gas Commission. 2021b. Petrinex volumetric data. Provided by BCOGC to Environment and Climate Change Canada [received 2021 Jul 30].
- [BCOGC] British Columbia Oil and Gas Commission. 2021c. Surface casing vent flow database [accessed 2021 Nov 18]. Available online at: https://reports.bcogc.ca/ogc/f?p=AMS_REPORTS:SCVF
- [BCOGC] British Columbia Oil and Gas Commission. 2021d. *Well index report* [accessed 2021 April 7]. Available online at: https://iris.bcogc.ca/download/well_index.csv
- [BCOGC] British Columbia Oil and Gas Commission. 2021e. *Well surface abandonment report* [accessed 2021 Sept 27]. Available online at: https://reports.bcogc.ca/ogc/app001/r/ams_reports/well-surface-abandonments

- [BCOGC] British Columbia Oil and Gas Commission. 2021f. *Well surface hole locations* [accessed 2021 Oct 20]. Available online at: https://data-bcogc.opendata.arcgis.com/datasets/9149cb556e694617970a5774621af8be_0.
- [CAPP] Canadian Association of Petroleum Producers. 1999. *CH₄ and VOC emissions from the Canadian upstream oil and gas industry*, Vols. 1 and 2. Publication No. 1999-0010. Prepared for the Canadian Association of Petroleum Producers. Calgary (AB): Clearstone Engineering Ltd.
- [CAPP] Canadian Association of Petroleum Producers. 2005a. *A national inventory of greenhouse gas (GHG), criteria air contaminant (CAC) and hydrogen sulphide (H₂S) emissions by the upstream oil and gas industry*, Vols. 1–5. Calgary (AB): Clearstone Engineering Ltd.
- [CAPP] Canadian Association of Petroleum Producers. 2005b. *Extrapolation of the 2000 UOG emission inventory to 2001, 2002 and 2003*. Calgary (AB): Clearstone Engineering Ltd.
- [CAPP] Canadian Association of Petroleum Producers. 2006. *An inventory of GHGs, CACs, and H₂S emissions by the Canadian bitumen industry: 1990 to 2003*. Vols. 1–3. Calgary (AB): Clearstone Engineering Ltd.
- [CAPP] Canadian Association of Petroleum Producers. 2007. *Best management practice - Management of fugitive emissions at upstream oil and gas facilities*. Available online at: <https://www.capp.ca/publications/best-management-practice-for-fugitive-emissions-management/>.
- [CAPP] Canadian Association of Petroleum Producers. 2014. *Update of fugitive equipment leak emission factors*. Prepared by Clearstone Engineering Ltd.
- [CAPP] Canadian Association of Petroleum Producers. 2021. *Statistical handbook for Canada's upstream petroleum industry* [accessed 2021 Oct 25]. Available online at: <https://www.capp.ca/resources/statistics/>.
- Carbon Limits. 2017. *Statistical analysis of leak detection and repair in Canada - Extension*. Prepared for Environment Canada. April 2017.
- [CER] Canada Energy Regulator. 2021. *Canada's energy future 2020* [accessed 2021 Oct 1]. Available online at: <https://apps.cer-rec.gc.ca/ftp/rrn/dc/dfl.aspx?GoCTemplateCulture=en-CA>.
- [CGA] Canadian Gas Association. 1997. *1995 air inventory of the Canadian natural gas industry*. Calgary (AB): Radian International LLC.
- Cenovus Energy. 2021. *Lloydminster upgrader throughput*. Unpublished report. Provided by Cenovus Energy to Environment and Climate Change Canada [2021 Oct 14].
- Cheminfo Services Inc. and Clearstone Engineering Ltd. 2014. *Compilation of a national inventory of greenhouse gas and fugitive VOC emissions by the Canadian coal mining industry*. Final report submitted to the Energy Group, Pollutant Inventories and Reporting Division, Environment Canada.
- Clearstone Engineering Ltd. and Carleton University. 2018. *Update of equipment, component and fugitive emission factors for Alberta upstream oil and gas*. Prepared for Alberta Energy Regulator by Clearstone Engineering Ltd. Calgary (AB).
- Clearstone Engineering Ltd. 2019. *2018 Alberta upstream oil & gas methane emissions inventory and methodology*. Prepared for Alberta Energy Regulator by Clearstone Engineering Ltd. Calgary (AB).
- [CNSOPB] Canada-Nova Scotia Offshore Petroleum Board. 2019. Production data [accessed 2019 Nov 7]. Available online at: <https://www.cnsopb.ns.ca/resource-library/weekly-activity-reports>.
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021a. *Production summary by well – Hebron* [revised 2021 Jan 18; accessed 2021 Oct 21]. Available online at: https://www.cnlopb.ca/wp-content/uploads/hebstats/heb_oil_2019.pdf.
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021b. *Production summary by well – Hibernia* [revised 2021 Jan 27; accessed 2021 Oct 21]. Available online at: https://www.cnlopb.ca/wp-content/uploads/hibstats/hib_oil_2019.pdf.
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021c. *Production summary by well – North Amethyst* [revised 2021 Jan 15; accessed 2021 Oct 21]. Available online at: https://www.cnlopb.ca/wp-content/uploads/nastats/na_oil_2019.pdf.
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021d. *Production summary by well – Terra Nova* [revised 2021 Jan 19; accessed 2021 Oct 21]. Available online at: https://www.cnlopb.ca/wp-content/uploads/tnstats/tn_oil_2019.pdf.
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021e. *Production summary by well – White Rose* [revised 2021 Jan 15; accessed 2021 Oct 21]. Available online at: https://www.cnlopb.ca/wp-content/uploads/wrstats/wr_oil_2019.pdf.
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021f. *Environment statistics – Spill frequency and volume annual summary* [revised 2021 Jan 7; accessed 2021 Oct 21]. Available online at: <https://www.cnlopb.ca/wp-content/uploads/spill/sumtab.pdf>.
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021g. *Monthly gas flaring*. Unpublished report. Provided by CNLOPB to Environment and Climate Change Canada [2021 Sep 20].
- [CNLOPB] Canada-Newfoundland and Labrador Offshore Petroleum Board. 2021h. *Schedule of wells summary* [accessed 2021 Nov 3]. Available online at: <https://www.cnlopb.ca/wells/>.
- [CPPI] Canadian Petroleum Products Institute. 2004. *Economic and environmental impacts of removing sulphur from Canadian gasoline and distillate production*. Calgary (AB): Levelton Consultants Ltd. in association with Purvin & Gertz Inc.

- [EC] Environment Canada. 2014. *Technical report on Canada's upstream oil and gas industry*. Vols. 1–4. Calgary (AB): Clearstone Engineering Ltd
- [ECCC] Environment and Climate Change Canada. 2017. *An inventory of GHG, CAC and other priority emissions by the Canadian oil sands industry: 2003 to 2015*. Vols 1–3. Calgary (AB): Clearstone Engineering Ltd.
- [ECCC] Environment and Climate Change Canada. 2018. *Regulations respecting reduction in the release of methane and certain volatile organic compounds (upstream oil and gas sector)* (SOR/2018-66). Available online: <https://pollution-waste.canada.ca/environmental-protection-registry/regulations/view?Id=146>
- [ECCC] Environment and Climate Change Canada. 2020a. *Canada-Alberta equivalency agreement respecting the release of methane from the oil and gas sector, 2020*. Available online: <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/agreements/equivalency/canada-alberta-methane-oil-gas.html>
- [ECCC] Environment and Climate Change Canada. 2020b. *Canada-British Columbia equivalency agreement respecting the release of methane from the oil and gas sector, 2020*. Available online: <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/agreements/equivalency/canada-british-columbia-methane-oil-gas.html>
- [ECCC] Environment and Climate Change Canada. 2020c. *Canada-Saskatchewan equivalency agreement respecting the release of methane from the oil and gas sector, 2020*. Available online at: <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/agreements/equivalency/canada-saskatchewan-methane-oil-gas.html>
- [ECCC] Environment and Climate Change Canada. 2021a. *Upstream oil and gas fugitive emissions model: Methodology and documentation*. Unpublished Report.
- [ECCC] Environment and Climate Change Canada. 2021b. Greenhouse Gas Reporting Program. Pre-release data. Available online at: <https://climate-change.canada.ca/facility-emissions/>.
- [EUB] Alberta Energy and Utilities Board. 2003. *ID 2003-01: Surface casing venting flow/gas migration testing, reporting, and repair requirements*. Available online at: <https://www.aer.ca/regulating-development/rules-and-directives/directives/id-2003-01>
- [GRI] Gas Research Institute. 2000. *Vented emissions from maintenance at natural gas distribution stations in Canada*. Austin (TX): Radian International LLC.
- Government of Alberta. 2021. Alberta Township Survey System [accessed 2021 Jan 14]. Available online at: <https://www.alberta.ca/alberta-township-survey-system.aspx>
- GreenPath Energy Ltd. 2016. *Modelling inputs for upstream oil and gas methane emission sources*. Prepared for Environment and Climate Change Canada.
- Hollingshead B. 1990. *Methane emissions from Canadian coal operations: A auantitative estimate*. Report CI 8936. Devon (AB): Coal Mining Research Company.
- Husky Energy Inc. 1998–2019. *Husky energy annual reports*. Available online at: https://huskyenergy.com/downloads/abouthusky/publications/annualreports/HSE_Annual2019.pdf.
- IHS Markit. 2018. Upstream oil and gas volumetric production accounting data.
- [IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, (eds). IGES (JP). Available online at: <http://www.ipcc-nccc.iges.or.jp/public/2006gl/index.html>.
- [IPCC] Intergovernmental Panel on Climate Change. 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Calvo Buendia E, Tanabe K, Kranjc A, Baasansuren J, Fukuda M, Ngarize S, Osako A, Pyrozhenko Y, Shermanau P, Federici S, (eds). IPCC (Switzerland). Available online at: <https://www.ipcc-nccc.iges.or.jp/public/2019rf/index.html>
- King B. 1994. *Management of methane emissions from coal mines: Environmental, engineering, economic and institutional implications of options*. Report prepared by Neill and Gunter for Environment Canada.
- [MB] Manitoba Government. 2021a. Petroleum industry spill statistics [revised 2021 Sep 15; accessed 2021 Oct 6]. Available online at: <http://www.gov.mb.ca/iem/petroleum/stats/spills.html>.
- [MB] Manitoba Government. 2021b. Petroleum statistics: Unique well identifier key list [accessed 2021 Nov 2]. Available online at: <http://www.manitoba.ca/iem/petroleum/reports/index.html>.
- [MB ARD] Manitoba Agriculture and Resource Development. 2021. Production reports [accessed 2021 Mar 10]. <https://www.gov.mb.ca/iem/petroleum/reports/index.html>.
- [NB NRED] New Brunswick Natural Resources and Energy Development. 2020. Well listing. Unpublished report. Provided by NB-NRED to Environment and Climate Change Canada [2020 May 21].
- [NB NRED] New Brunswick Natural Resources and Energy Development. 2021. Monthly production statistics [accessed 2021 Oct 18]. Available online at: https://www2.gnb.ca/content/dam/gnb/Departments/en/pdf/Minerals-Minerales/Monthly_Statistics.pdf.
- [OGSRL] Oil, Gas & Salt Resources Library. 2020. Petroleum well data – Ontario [accessed 2020 Oct 23]. Available online at: http://www.ogsrlibrary.com/data_free_petroleum_ontario.
- ORTECH Consulting Inc. 2013. *Canadian natural gas companies 2005 and 2011 greenhouse gas and criteria air contaminant inventory report and validation by audit*. Guelph (ON): CEPEI.
- Petrinex. 2021. Petrinex: Canada's petroleum information network. Alberta Public Data - Monthly Conventional Volumetric Data [cited 2021 Jul 13]. <https://www.petrinex.ca/Pages/default.aspx>.
- Prasino Group. 2013. Final Report for Determining Bleed Rates for Pneumatic Devices in British Columbia. December 2013.

- [SK] Government of Saskatchewan. 2020. *The Oil and Gas Emissions Management Regulations (OGEMR) [Amended 2020]*. <https://publications.saskatchewan.ca/api/v1/products/92804/formats/109853/download>
- [SK MER] Saskatchewan Ministry of Energy and Resources. 1990–2008. *Mineral statistics yearbook*. Petroleum and Natural Gas. Available online at: <https://publications.saskatchewan.ca/#/products/82350>.
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2009–2011. *Annual petroleum statistics*. Available online at: <https://publications.saskatchewan.ca/#/categories/2540>.
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2019. *Guideline PNG035: Estimating venting and fugitive emissions, Version 1.0*. Available online at: <https://publications.saskatchewan.ca/api/v1/products/103639/formats/114982/download>
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2020. *Directive PNG017: Measurement requirements for oil and gas operations, Revision 4.0*. September 2020. <https://publications.saskatchewan.ca/api/v1/products/105418/formats/117680/download>
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2012–2020a. *Crude oil volume and value summary* [accessed 2021 Jul 12]. Available online at: <https://publications.saskatchewan.ca/#/categories/1241>.
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2012–2020b. *Natural gas volume and value summary* [accessed 2021 Jul 12]. Available online at: <https://publications.saskatchewan.ca/#/categories/1242>.
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2012–2020c. *Saskatchewan fuel, flare and vent* [accessed 2021 Jul 16]. Available online at: <https://publications.saskatchewan.ca/#/categories/2541>.
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2021a. *Saskatchewan upstream oil and gas IRIS incident report* [revised 2021 Sep 9; accessed 2021 Oct 5]. Available online at: <http://publications.saskatchewan.ca/api/v1/products/78193/formats/87695/download>.
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2021b. *Gas composition by production class*. Unpublished. Provided to Environment and Climate Change Canada [2021 Jul 13].
- [SK MER] Saskatchewan Ministry of Energy and Resources. 2021c. *Gas plant reports* [accessed 3 Jun 2021]. Available online at: <https://publications.saskatchewan.ca/#/categories/2542>.
- Spartan Controls. 2018. *Pneumatic vent gas measurement*. Prepared for Petroleum Technology Alliance of Canada (PTAC).
- Statistics Canada. 1990– . *Report on energy supply and demand in Canada*. Catalogue No. 57-003-X. Available online at: <http://www5.statcan.gc.ca/olc-cel/olc.action?objId=57-003-X&objType=2&lang=en&limit=0>.
- Statistics Canada. 1999–2002. *Coal and coke statistics*. Catalogue No. 45-002-X. Available online at: <https://www150.statcan.gc.ca/n1/en/catalogue/45-002-X>.
- Statistics Canada. 2020. Gas pipeline distance, by province. Unpublished database. Provided to Environment and Climate Change Canada [2019 Dec].
- Statistics Canada. No date [a]. Table 25-10-0047-01 (formerly CANSIM 131-0001) – Natural gas, monthly supply and disposition. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510004701>.
- Statistics Canada. No date [b]. Table 25-10-0055-01 (formerly CANSIM 131-0004) – Supply and disposition of natural gas, monthly. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510005501>.
- Statistics Canada. No date [c]. Table 25-10-0014-01 (formerly CANSIM 126-0001) – Crude oil and equivalent, monthly supply and disposition. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510001401>.
- Statistics Canada. No date [d]. Table 25-10-0063-01 (formerly CANSIM 126-0003) – Supply and disposition of crude oil and equivalent. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510006301>.
- Statistics Canada. No date [e]. Table 25-10-0057-01 (formerly CANSIM 129-0005) – Canadian natural gas storage, Canada and provinces. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510005701>.
- Statistics Canada. No date [f]. Table 25-10-0032-01 (formerly CANSIM 129-0002) – Natural gas utilities, monthly receipts and disposition. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510003201>.
- Tyner D. and Johnson M. 2020. Improving upstream oil and gas emissions estimates with updated gas composition data. Carleton University (ON): Energy and Emissions Research Laboratory (EERL). Prepared for Environment and Climate Change Canada.
- [US EPA] United States Environmental Protection Agency. 1995. Protocol for equipment leak emission estimates.
- [US EPA] Environmental Protection Agency. 2004. Methane emissions from abandoned coal mines in the United States: Emission inventory methodology and 1990-2002 emissions estimates.
- [YK] Yukon Government. 2020. Energy, mines and resources: Yukon well listing [revised 2014 May; accessed 2020 Oct 26]. Available online at: <https://yukon.ca/en/yukon-well-listing>.

Annex 3.3, Methodology for the Industrial Processes and Product Use Sector

Cheminfo Services. 2005a. *Improvements to Canada's greenhouse gas emissions inventory related to non-energy use of hydrocarbon products*. Unpublished report. Markham (ON): Cheminfo Services Inc.

Cheminfo Services. 2005b. *Improving and updating industrial process-related activity data and methodologies used in Canada's greenhouse gas inventory, hydrofluorocarbons (HFCs)*. Unpublished report. Markham (ON): Cheminfo Services Inc.

Cheminfo Services. 2006. *Improvements and updates to certain industrial process and solvent use-related sections in Canada's greenhouse gas inventory*. Unpublished report. Markham (ON): Cheminfo Services Inc.

- [CSPA] Canadian Steel Producers Association. 2013–2017. *Annual Canadian iron and steel production and disposition data*. Unpublished data.
- [EHS] Environmental Health Strategies Inc. 2013. *Report on emission factors for HFCs in Canada*. Unpublished report. Toronto (ON): Environmental Health Strategies Inc. Prepared for Environment Canada.
- [ECCC] Environment and Climate Change Canada. 2015a. 2008 – 2012 HFC sales data collected under the *Canadian Environmental Protection Act, 1999*, section 71: Notice with respect to hydrofluorocarbons. *Canada Gazette* Part 1, vol. 148, no. 16, p. 920–930. Program Development and Engagement Division. Unpublished, confidential data.
- [ECCC] Environment and Climate Change Canada. 2015b. *Review of country-specific HFCs emission estimations in the refrigeration and air conditioning sectors*. Unpublished report. Ottawa (ON).
- [ECCC] Environment and Climate Change Canada. 2016a. 2013–2014 HFC sales data collected under the *Canadian Environmental Protection Act, 1999*, section 71: Notice with respect to hydrofluorocarbons in bulk. *Canada Gazette* Part 1, vol. 150, no. 1, p 7–13. Program Development and Engagement Division. Unpublished, confidential data.
- [ECCC] Environment and Climate Change Canada. 2016b. 2015 HFC sales data collected under the *Canadian Environmental Protection Act, 1999*, section 71: Notice with respect to hydrofluorocarbons in bulk. *Canada Gazette* Part 1, vol. 150, no. 24, p. 1816–1823. Program Development and Engagement Division. Unpublished, confidential data.
- [ECCC] Environment and Climate Change Canada. 2017. Table 1: Facilities that make up the iron, steel and ilmenite smelting sector under the *Canadian Environmental Protection Act, 1999*, subsection 56(1): Notice requiring the preparation and implementation of pollution prevention plans in respect of specified toxic substances released from the iron, steel and ilmenite sector. *Canada Gazette* Part I, vol. 150, no. 22. Available online at: <http://www.gazette.gc.ca/rp-pr/p1/2017/2017-05-06/html/sup2-eng.html>.
- [ECCC] Environment and Climate Change Canada. 2021. 2017–2020 HFC bulk import and export data collected under the *Canadian Environmental Protection Act, 1999*, Ozone-depleting Substances and Halocarbon Alternatives Regulations: *Canada Gazette* Part II, vol. 150, no. 13, p 1613–1678. Ozone Layer Protection and Export Controls. Unpublished, confidential data.
- [EC] Environment Canada and Canadian Electricity Association. 2008. *SF₆ emission estimation and reporting protocol for electric utilities*. Available online at: <http://www.publications.gc.ca/site/eng/454401/publication.html>.
- [GHGRP] Greenhouse Gas Reporting Program. 2018–2020. *Expanded sector-specific data*. Unpublished data.
- [IPCC] Intergovernmental Panel on Climate Change. 2006. *Guidelines for national greenhouse gas inventories*. Available online at: <http://www.ipcc-nccc.iges.or.jp/public/2006gl/index.html>.
- McCann TJ. 2000. *1998 fossil fuel and derivative factors*. Unpublished report. Prepared by TJ McCann and Associates for Environment Canada.
- [NRCan] Natural Resources Canada. 1990–2006. *Canadian Minerals Yearbook*. Minerals and Metals Sector (Annual). Natural Resources Canada (discontinued).
- [NRCan] Natural Resources Canada. 2007–2019. *Canada, production of limestone – stone*. Unpublished data. Natural Resources Canada, Mineral & Mining Statistics Division.
- Statistics Canada. 1990–2003. *Primary iron and steel*. Monthly. Catalogue No. 41-001-XIB (discontinued).
- Statistics Canada. 1990–2020. *Industrial chemicals and synthetic resins*. Catalogue No. 46-002-XIE. Available online (only 2008 to 2020) at: <https://www150.statcan.gc.ca/n1/daily-quotidien/200814/dq200814d-eng.htm>.
- Statistics Canada. 1990–2020. *Report on energy supply and demand in Canada*. Catalogue No. 57-003-XIB. Available online at: <https://www150.statcan.gc.ca/n1/en/catalogue/57-003-X>.
- Statistics Canada. 2004–2012. *Steel, tubular products and steel wire*. Monthly. Catalogue No. 41-019-X (discontinued).
- ### Annex 3.4, Methodology for the Agriculture Sector
- [AAFRD] Alberta Agriculture, Food and Rural Development. 2001. Alberta Cow-Calf Audit, 1997/1998 Production indicators and management practices over the last 10 Years. Edmonton (AB).
- [AAFRD and University of Alberta] Alberta Agriculture, Food and Rural Development and University of Alberta. 2003. *Development of a farm-level greenhouse gas assessment: Identification of knowledge gaps and development of a science plan* [accessed 2015 December 4]. AARI Project No. 2001 J204. Available online at: [http://www1.agric.gov.ab.ca/\\$Department/deptdocs.nsf/all/cf9706/\\$FILE/ghgreport.pdf](http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/cf9706/$FILE/ghgreport.pdf).
- [AAFC] Agriculture and Agri-Food Canada. 2018. Red meat conversion factors. Available online at: <https://www.agr.gc.ca/eng/canadas-agriculture-sectors/animal-industry/red-meat-and-livestock-market-information/carcass-weight/conversion-factors/?id=1415860000020>.
- [AAFC] Agriculture and Agri-Food Canada. No date [a]. *Red meat and livestock market information* [accessed 2018 October 31]. Available online at: <https://agriculture.canada.ca/en/canadas-agriculture-sectors/animal-industry/red-meat-and-livestock-market-information>.
- [AAFC] Agriculture and Agri-Food Canada. No date [b]. Average Warm Carcass Weights of Federally Inspected Plants – (in lbs.) [accessed 2021 October 26]. Available online at: <http://aimis-simia.agr.gc.ca/rp/index-eng.cfm?menupos=1.02.08&pdctc=&r=135&action=pR&LANG=EN>.
- Appuhamy JADRN, France J, Kebreab E. 2016. Models for predicting enteric methane emissions from dairy cows in North America, Europe, and Australia and New Zealand. *Global Change Biology*, 22(9): 3039–3056.

- Arrouays D, Saby N, Walter C, Lemercier B, Schwartz C. 2006. Relationships between particle-size distribution and organic carbon in French arable topsoils. *Soil Use and Management*, 22: 48–51.
- Baral, KR, Jayasundara S, Brown S, and Wagner-Riddle C. 2021. Long-term variability in N₂O emissions and emission factors from corn and soybeans induced by weather and management (in press.)
- Beauchemin KA, McGinn SM. 2005. Methane emissions from feedlot cattle fed barley or corn diets. *Journal of Animal Science*, 83: 653–661.
- Beauchemin KA, McGinn SM. 2006. Enteric methane emissions from growing beef cattle as affected by diet and level of intake. *Canadian Journal of Animal Science*, 86(3): 401–408.
- Beauchemin KA, McGinn SM, Benchaar C, Holtshausen L. 2009. Crushed sunflower, flax, or canola seeds in lactating dairy cow diets: Effects on methane production, rumen fermentation, and milk production. *Journal of Dairy Science*, 92: 2118–2127.
- Boadi DA, Ominski KH, Fulawka DL, Wittenberg KM. 2004a. *Improving estimates of methane emissions associated with enteric fermentation of cattle in Canada by adopting an IPCC tier-2 methodology*. Final report. Prepared by the Department of Animal Science, University of Manitoba for the Greenhouse Gas Division, Environment Canada. Winnipeg (MB): University of Manitoba.
- Boadi DA, Wittenberg KM. 2002. Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF₆) tracer gas technique. *Canadian Journal of Animal Science*, 82: 201–206.
- Boadi DA, Wittenberg KM, McCaughey WP. 2002. Effects of grain supplementation on methane production of grazing steers using the sulphur (SF₆) tracer gas technique. *Canadian Journal of Animal Science*, 82: 151–157.
- Boadi DA, Wittenberg KM, Scott SL, Burton D, Buckley K, Small JA, Ominski KH. 2004b. Effect of low and high forage diet on enteric and manure pack greenhouse gas emissions from a feedlot. *Canadian Journal of Animal Science*, 84: 445–453.
- Bouwman AF. 1996. Direct emission of nitrous oxide from agricultural soils. *Nutrient Cycling in Agroecosystems*, 46: 53–70.
- Bouwman AF, Boumans LJM, Batjes NH. 2002a. Emissions of N₂O and NO from fertilized fields: Summary of available data. *Global Biogeochemical Cycles*, 16: 6-1–6-13.
- Bouwman AF, Boumans LJM, Batjes NH. 2002b. Estimation of global NH₃ volatilization loss from synthetic fertilizers and animal manure applied to arable lands and grassland. *Global Biogeochemical Cycles*, 16: 8.1–8.15.
- BPR-Infrastructure inc. 2008. *Suivi 2007 du Portrait agroenvironnemental des fermes du Québec* [accessed 2015 December 4]. Prepared for the Quebec Ministère de l'Agriculture, des Pêcheries et de l'Alimentation, the Union des producteurs agricoles and Agriculture and Agri-Food Canada. Available online at: <http://www.mapaq.gouv.qc.ca/fr/md/Publications/Pages/Details-Publication.aspx?guid=%7B3fcc5e09-ea9f-4cfa-a4db-91beff2a993b%7D>.
- Canfax Research Services. 2009. *Trends, cycles and seasonality in the cattle industry*. Calgary (AB): Canadian Cattlemen's Association. 36 pp.
- [CCME] Canadian Council of Ministers of the Environment. 2010. *Review of the current Canadian legislative framework for wastewater biosolids*. Canadian Council of Ministers of the Environment (CCMC). PN 1446. ISBN 978-1-896997-95-7 PDF. 65 p.
- Chadwick DR, Sneath RW, Phillips VR, Pain BF. 1999. A UK inventory of nitrous oxide emissions from farmed livestock. *Atmospheric Environment*, 33: 3345–3354.
- Chai L, Kröbel R, MacDonald D, Bittman S, Beauchemin KA, Janzen HH, McGinn SM, Vanderzaag A. 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. *Atmospheric Environment*, 126: 1–14.
- Chang C, Janzen HH. 1996. Long-term fate of nitrogen from annual feedlot manure applications. *Journal of Environmental Quality*, 25: 785–790.
- Chaves AV, Thompson LC, Iwaasa AD, Scott SL, Olson ME, Benchaar C, Veira DM, McAllister TA. 2006. Effect of pasture type (alfalfa vs. grass) on methane and carbon dioxide production by yearling beef heifers. *Canadian Journal of Animal Science*, 86(3): 409–418.
- Cheminfo Services Inc. 2017. *Study of the typical management and disposal practices of wastewater treatment sludge in Canada and impacts on municipal solid waste landfills*. Internal report. Gatineau (QC): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- Cheminfo Services Inc. 2018. *Estimating the generation and management of municipal wastewater treatment sludge in Canada between 1990 and 2015*. Internal report. Gatineau (QC): Environment Climate Change Canada.
- Christensen DA, Steacy G, Crowe WL. 1977. Nutritive value of whole crop cereal silages. *Canadian Journal of Animal Science*, 57: 803–805.
- Coote DR, Liang BC, Huffman EC. 2008. *Crop residue burning in Canada*. Gatineau (QC): Greenhouse Gas Division, Environment Canada.
- Corre MD, Pennock DJ, Van Kessel C, Elliott DK. 1999. Estimation of annual nitrous oxide emissions from a transitional Grassland–Forest region in Saskatchewan, Canada. *Biogeochemistry*, 44: 29–49.
- Corre MD, Van Kessel C, Pennock DJ. 1996. Landscape and seasonal patterns of nitrous oxide emissions in a semiarid region. *Soil Science Society of America Journal*, 60: 1806–1815.
- [CRAAQ] Centre de référence en agriculture et agroalimentaire du Québec. 1999. Chèvres laitières—Budget: Production laitière. Agdex 435/821.

- da Sylva AP, Kay BD. 1997. Estimating the least limiting water range of soils from properties and management. *Soil Science Society of America Journal*, 61: 877–883.
- Dad K, Wahid AK, Khan AA, Anwar A, Ali M, Sarwar N, Ali S, Ahmad A, Ahmad M, Khan KA, et al. 2018. Nutritional status of different biosolids and their impact on various growth parameters of wheat (*Triticum aestivum* L.). *Saudi Journal of Biological Sciences*, 26: 1423–1428.
- Decisioneering Inc. 2000. Crystal Ball®, Decisioneering Inc., Denver, Colorado, U.S.A. [accessed 2015 December 4]. Available online at: <http://www.crystalball.com>.
- Desjardins RL, Worth DE, Pattey E, VandenZaag A, Srinnivasan R, Worthy D, Sweeney C, Metzger S. 2018. The challenge of reconciling bottom-up agricultural methane emissions inventories with top-down measurements. *Agricultural and Forest Meteorology Journal*, 248: 48–59.
- Dobbie KE, McTaggart IP, Smith KP. 1999. Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables and mean emission factors. *Journal of Geophysical Research*, 104: 26891–26899.
- [EDI] Environmental Dynamics Inc. 2017. *Beneficial reuse of biosolids jurisdictional review* [accessed 2019 May 25]. Available online at: https://www.crd.bc.ca/docs/default-source/irm-reports/consolidationreportnov17/appendixq.pdf?sfvrsn=d99609ca_2.
- Ellis JL, Bannink A, France J, Kebreab E, Dijkstra J. 2010. Evaluation of enteric methane prediction equations for dairy cows used in whole farm models. *Global Change Biology*, 16: 3246–3256.
- Ellis JL, Kebreab E, Odongo NE, Beauchemin K, McGinn S, Nkrumah JD, Moore SS, Christopherson R, Murdoch GK, McBride BW, et al. 2009. Modeling methane production from beef cattle using linear and nonlinear approaches. *Journal of Animal Science*, 87: 1334–1345.
- Ellis JL, Kebreab E, Odongo NE, McBride BW, Okine EK, France J. 2007. Prediction of methane production from dairy and beef cattle. *Journal of Dairy Science*, 90: 3456–3467.
- Environment Canada. 2002. Canadian climate normals—precipitation [accessed 2015 December 4]. Available online at: http://climate.weather.gc.ca/climate_normals/index_e.html.
- Escobar-Bahamondes P, Oba M, Kröbel R, McAllister TA, MacDonald D, Beauchemin KA. 2017. Estimating enteric methane production for beef cattle using empirical prediction models compared with IPCC Tier 2 methodology. *Canadian Journal of Animal Science*, 97: 599–612.
- Eugène M, Massé D, Chiquette J, Benchaar C. 2008. Meta-analysis on the effects of lipid supplementation on methane production in lactating dairy cows. *Canadian Journal of Animal Science*, 88: 331–334.
- Flynn HC, Smith JO, Smith KA, Wright J, Smith P, Massheder J. 2005. Climate- and crop-responsive emission factors significantly alter estimates of current and future nitrous oxide emissions from fertilizer use. *Global Change Biology*, 11: 1522–1536.
- Farm & Food Care Ontario. 2013. Facts & figures about Canadian dairy cows, Farm Food Care Ontario. Available online at: <https://www.farmfoodcareon.org/wp-content/uploads/2017/05/Fact-Sheet-Dairy-2016.pdf>.
- Freibauer A. 2003. Regionalized inventory of biogenic greenhouse gas emissions from European agriculture. *European Journal of Agronomy*, 19: 135–160.
- Godbout S, Verma M, Larouche JP, Potvin L, Chapman AM, Lemay SP, Pelletier F, Brar SK. 2010. Methane production potential (B_0) of swine and cattle manures – A Canadian perspective. *Environmental Technology*, 31: 1371–1379.
- Goss MJ, Goorahoo D. 1995. Nitrate contamination of groundwater: measurement and prediction. *Fertilizer Research*, 42: 331–338.
- Grant R, Pattey E. 1999. Mathematical modeling of nitrous oxide emissions from an agricultural field during spring thaw. *Global Biogeochemical Cycles*, 13: 679–694.
- Gregorich EG, Rochette P, VandenBygaart AJ, Angers DA. 2005. Greenhouse gas contributions of agricultural soils and potential mitigation practices in eastern Canada. *Soil & Tillage Research*, 76: 1–20.
- Hao X. 2007. Nitrate accumulation and greenhouse gas emissions during compost storage. *Nutrient Cycling in Agroecosystems*, 78: 189–195.
- Hao X, Benke M, Larney FJ, McAllister TA. 2010a. Greenhouse gas emissions when composting manure from cattle fed wheat dried distillers' grains with solubles. *Nutrient Cycling in Agroecosystems*, 89: 105–114.
- Hao X, Chang C, Carefoot JM, Janzen HH, Ellert BH. 2001a. Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutrient Cycling in Agroecosystems*, 60: 1–8.
- Hao X, Chang C, Larney FJ, Travis GR. 2001b. Greenhouse gas emissions during cattle feedlot manure composting. *Journal of Environmental Quality*, 30: 376–386.
- Hao X, Stanford K, McAllister TA, Larney FJ, Xu S. 2009. Greenhouse gas emissions and final compost properties from co-composting bovine specified risk material and mortalities with manure. *Nutrient Cycling in Agroecosystems*, 83: 289–299.
- Hao X, Xu S, Larney FJ, Stanford K, Cessna AJ, McAllister TA. 2010b. Inclusion of antibiotics in feed alters greenhouse gas emissions from feedlot manure during composting. *Nutrient Cycling in Agroecosystems*, 89: 257–267.
- Hao X, Xu S, McAllister TA, Larney FJ. 2008. Antibiotics in cattle diet affect greenhouse gas emissions from manure composting. *Australian Journal of Experimental Agriculture*, 48: 342–355.
- Hénault C, Devis X, Page S, Justes E, Reau R, Germon J-C. 1998. Nitrous oxide emissions under different soil and land management conditions. *Biology and Fertility of Soils*, 26: 199–207.

- Hutchings NJ, Sommer SG, Andersen JM, Asman WAH. 2001. A detailed ammonia emission inventory for Denmark. *Atmospheric Environment*, 35: 1959–1968.
- Hybrid. 2001. Hybrid converter—commercial hens and toms [accessed 2015 December 4]. Available online at: <https://www.hybridturkeys.com/en/about-us/breeding-and-distribution/>.
- Hydromantis Ltd. 2007. GPS-X 5.0 software. General Purpose Simulator — default parameters.
- [IPCC] Intergovernmental Panel on Climate Change. 2000. *Good practice guidance and uncertainty management in national greenhouse gas inventories* [accessed 2015 December 4]. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at: <http://www.ipcc-nccc.iges.or.jp/public/gp/english/>.
- [IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC guidelines for national greenhouse gas inventories* [accessed 2015 December 4]. Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change. Available online at: <http://www.ipcc-nccc.iges.or.jp/public/2006gl/vol4.html>.
- [IPCC] Intergovernmental Panel on Climate Change. 2019. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories* [accessed 2020 May 22]. Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change. Available online at: <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>
- [IPCC/OECD/IEA] Intergovernmental Panel on Climate Change, Organisation for Economic Co-operation and Development, and International Energy Agency. 1997. *Revised 1996 IPCC guidelines for greenhouse gas inventories* [accessed 2015 December 4]. Available online at: <http://www.ipcc-nccc.iges.or.jp/public/gl/invs1.html>.
- Izaurrealde RC, Lemke RL, Goddard TW, McConkey B, Zhang Z. 2004. Nitrous oxide emissions from agricultural toposequences in Alberta and Saskatchewan. *Soil Science Society of America Journal*, 68: 1285–1294.
- Jambert C, Delmas R, Serça D, Thouron L, Labroue L, Delprat L. 1997. N₂O and CH₄ emissions from fertilized agricultural soils in southwest France. *Nutrient Cycling in Agroecosystems*, 48: 105–114.
- Janzen HH, Beauchemin KA, Bruinsma Y, Campbell CA, Desjardins RL, Ellert BH, Smith EG. 2003. The fate of nitrogen in agroecosystems: an illustration using Canadian estimates. *Nutrient Cycling in Agroecosystems*, 67: 85–102.
- Jayasundara S, Ranga Niroshan Appuhamy JAD, Kebreab E, Wagner-Riddle C. 2016. Methane and nitrous oxide emissions from Canadian dairy farms and mitigation options: An updated review. *Canadian Journal of Animal Science*, 96(3): 306–331.
- Jayasundara S, Wagner-Riddle C. 2014. Greenhouse gas emissions intensity of Ontario milk production in 2011 compared with 1991. *Canadian Journal of Animal Science*, 94: 155–173.
- Kaharabata SK, Schuepp PH, Desjardins RL. 1998. Methane emissions from above ground open manure slurry tanks. *Global Biogeochemical Cycles*, 12: 545–554.
- Karimi-Zindashty Y, Macdonald JD, Desjardins RL, Worth D, Hutchinson JJ, Vergé XPC. 2012. Sources of uncertainty in the IPCC Tier 2 Canadian livestock model. *The Journal of Agricultural Science*, 150(5): 556–569.
- Karimi-Zindashty Y, Macdonald JD, Desjardins RL, Worth D, Liang BC. 2014. *Determining the uncertainty in agricultural nitrous oxide emissions for Canada*. Internal report. Gatineau (QC): Greenhouse Gas Division, Environment Canada.
- Kebreab E, Clark K, Wagner-Riddle C, France J. 2006. Methane and nitrous oxide emissions from Canadian animal agriculture: A review. *Canadian Journal of Animal Science*, 86: 135–158.
- Kononoff PJ, Mustafa AF, Christensen DA, McKinnon JJ. 2000. Effects of barley silage particle length and effective fiber on yield and composition of milk from dairy cows. *Canadian Journal of Animal Science*, 80: 749–752.
- Kopp JC, Wittenberg KM, McCaughey WP. 2004. Management strategies to improve cow-calf productivity on meadow bromegrass pastures. *Canadian Journal of Animal Science*, 84(3): 529–535.
- Koroluk R, Bourque L. 2003. *Manure storage in Canada*. Statistics Canada [accessed 2010 May]. Catalogue No. 21-021-MIE2003001, Vol. 1, No. 1. Available on line at <http://publications.gc.ca/Collection/Statcan/21-021-M/21-021-MIE2003001.pdf>
- Lactanet. 2020. Statistics from milk recording data (database). Vision 2000.
- Laguë C, Gaudet É, Agnew J, Fonstad TA. 2005. Greenhouse gas emissions from liquid swine manure storage facilities in Saskatchewan. *Transactions of the American Society of Agricultural Engineers*, 48: 2289–2296.
- Lemke RL, Baron V, Iwaasa A, Farrell R, Schoenau J. 2012. *Quantifying nitrous oxide emissions resulting from animal manure on pasture, range and paddock by grazing cattle in Canada*. Final report. Prepared by Agriculture and Agri-Food Canada for the Greenhouse Gas Division, Environment Canada. Saskatoon (SK).
- Lemke RL, Izaurrealde RC, Nyborg M, Solberg ED. 1999. Tillage and N-source influence soil-emitted nitrous oxide in the Alberta Parkland Region. *Canadian Journal of Soil Science*, 79: 15–24.
- Liang BC. 2014. *Estimating ammonia emissions from synthetic nitrogen fertilizer application in Canada*. Gatineau (QC): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- Liang BC, Padbury G, Patterson G. 2004. *Cultivated organic soils in Canada*. Gatineau (QC): Greenhouse Gas Division, Environment Canada.
- Liebig MA, Morgan JA, Reeder JD, Ellert BH, Gollany HT, Schuman GE. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil & Tillage Research*, 83: 25–52.

- MacDonald JD, Liang BC. 2011. *Analysis of Canadian quantification methodologies of greenhouse gas emissions from livestock: IPCC Tier 2 quality control documentation 2011 submission*. Internal report submitted to Dominique Blain. Gatineau (QC): Greenhouse Gas Division, Environment Canada.
- MacMillan RA, Pettapiece WW. 2000. *Alberta landforms: Quantitative morphometric descriptions and classification of typical Alberta landforms*. Semiarid Prairie Agricultural Research Centre, Research Branch, Agriculture and Agri-Food Canada, Swift Current, Saskatchewan, Canada, Technical Bulletin No. 2000-2E.
- Manitoba Agriculture and Food. 2000. *Manitoba cattle on feed 1999/2000*. Market Analysis and Statistics Section, Program and Policy Analysis Branch, Manitoba Agriculture and Food.
- Marinier M, Clark K, Wagner-Riddle C. 2004. *Improving estimates of methane emissions associated with animal waste management systems in Canada by adopting an IPCC Tier-2 methodology*. Final report. Prepared by the Department of Land Resource Science, University of Guelph for the Greenhouse Gas Division, Environment Canada, by the Department of Land Resource Science. Guelph (ON): University of Guelph.
- Marinier M, Clark K, Wagner-Riddle C. 2005. *Determining manure management practices for major domestic animals in Canada*. Final report. Prepared by the Department of Land Resource Science, University of Guelph for the Greenhouse Gas Division, Environment Canada., Guelph (ON): University of Guelph.
- Massé DI, Croteau F, Patni NK, Masse L. 2003. Methane emissions from dairy cow and swine manure slurries stored at 10°C and 15°C. *Canadian Biosystems Engineering*, 45: 6.1–6.6.
- Massé DI, Masse L, Claveau S, Benchaar C, Thomas O. 2008. Methane emissions from manure storages. *Transactions of the ASABE*, 51: 1775–1781.
- McCaughay WP, Wittenberg K, Corrigan D. 1997. Methane production by steers on pasture. *Canadian Journal of Animal Science*, 77: 519–524.
- McCaughay WP, Wittenberg K, Corrigan D. 1999. Impact of pasture type on methane production by lactating beef cows. *Canadian Journal of Animal Science*, 79: 221–226.
- McGinn SM, Beauchemin KA, Coates T, Colomboatto D. 2004. Methane emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. *Journal of Animal Science*, 82: 3346–3356.
- McGinn SM, Chen D, Loh Z, Hill J, Beauchemin KA, Denmead OT. 2008. Methane emissions from feedlot cattle in Australia and Canada. *Australian Journal of Experimental Agriculture*, 48: 183–185.
- McGinn SM, Chung YH, Beauchemin KA, Iwaasa AD, Grainger C. 2009. Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle. *Canadian Journal of Animal Science*, 89: 409–413.
- Milne AE, Glendining MJ, Bellamy P, Misselbrook T, Gilhespy S, Rivas Casado M, Hulin A, van Oijen M, Whitmore AP. 2014. Analysis of uncertainties in the estimates of nitrous oxide and methane emissions in the UK's greenhouse gas inventory for agriculture. *Atmospheric Environment*, 82: 94–105.
- Minasny B, McBratney AB, Bristow KL. 1999. Comparison of different approaches to the development of pedotransfer functions for water-retention curves. *Geoderma*, 93: 225–253.
- Monni S, Perälä P, Regina K. 2007. Uncertainty in agricultural CH₄ and N₂O emissions from Finland – Possibilities to increase accuracy in emission estimates. *Mitigation and Adaptation Strategies for Global Change*, 12: 545–571.
- [NRC] National Research Council (U.S.). 1981. *Nutrient requirements of goats*. Washington (DC): National Research Council, National Academy Press.
- [NRC] National Research Council (U.S.). 1985. *Nutrient requirements of sheep*. 6th revised edition. Washington (DC): National Research Council, National Academy Press.
- [NRC] National Research Council (U.S.). 1989. *Nutrient requirements of horses*. 5th revised edition. Washington (DC): National Research Council, National Academy Press.
- [NRC] National Research Council (U.S.). 1998. *Nutrient requirements of swine*. 10th revised edition. Washington (DC): National Research Council, National Academy Press.
- [NRC] National Research Council (U.S.). 2001. *Nutrient requirements of dairy cattle*. 7th revised edition. Washington (DC): National Research Council, National Academy Press.
- Nyborg M, Solberg ED, Izaurrealde RC, Malhi SS, Molina-Ayala M. 1995. Influence of long-term tillage, straw and N fertilizer on barley yield, plant-N uptake and soil-N balance. *Soil & Tillage Research*, 36: 165–174.
- Odongo NE, Bagg R, Vessie G, Dick P, Or-Rashid MM, Hook SE, Gray JT, Kebreab E, France J, McBride BW. 2007. Long-term effects of feeding monensin on methane production in lactating dairy cows. *Journal of Dairy Science*, 90: 1781–1788.
- Okine EK, Mathison GW. 1991. Effects of feed intake on particle distribution, passage of digesta, and extent of digestion in the gastrointestinal tract of cattle. *Journal of Animal Science*, 69: 3435–3445.
- Ominski KH, Boadi DA, Wittenberg KM. 2006. Enteric methane emissions from backgrounded cattle consuming all-forage diets. *Canadian Journal of Animal Science*, 86: 393–400.
- Park KH, Thompson AG, Marinier M, Clark K, Wagner-Riddle C. 2006. Greenhouse gas emissions from stored liquid swine manure in a cold climate. *Atmospheric Environment*, 40: 618–627.
- Park KH, Wagner-Riddle C, Gordon RJ. 2010. Comparing methane fluxes from stored liquid manure using micrometeorological mass balance and floating chamber methods. *Agricultural and Forest Meteorology*, 150: 175–181.

- Pattey E, Trzcinski MK, Desjardins RL. 2005. Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure. *Nutrient Cycling in Agroecosystems*, 72: 173–187.
- Paul JW, ZebARTH BJ. 1997. Denitrification and nitrate leaching during the fall and winter following dairy cattle slurry application. *Canadian Journal of Soil Science*, 77: 231–240.
- Pennock DJ, Corre MD. 2001. Development and application of landform segmentation procedures. *Soil & Tillage Research*, 58: 151–162.
- Petit HV, Dewhurst RJ, Proulx JG, Khalid M, Haresign W, Twagiramungu H. 2001. Milk production, milk composition, and reproductive function of dairy cows fed different fats. *Canadian Journal of Animal Science*, 81: 263–271.
- Rochette P, Chantigny MH, Ziadi N, Angers, DA, Bélanger G, Charbonneau E, Pellerin D, Liang BC, Bertrand N. 2014. Soil nitrous oxide emissions after deposition of dairy cow excreta in eastern Canada. *Journal of Environmental Quality*, 43: 829–841.
- Rochette P, Janzen HH. 2005. Towards a revised coefficient for estimating N₂O from legumes. *Nutrient Cycling in Agroecosystems*, 73: 171–179.
- Rochette P, Worth DE, Lemke RL, McConkey BG, Pennock DJ, Wagner-Riddle C, Desjardins RL. 2008. Estimation of N₂O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. *Canadian Journal of Soil Science*, 88: 641–654.
- Rotz CA. 2004. Management to reduce nitrogen losses in animal production. *Journal of Animal Science*, 82(Suppl.): E119–E137.
- Rypdal K, Winiwarter W. 2001. Uncertainties in greenhouse gas emission inventories – Evaluation, comparability and implications. *Environmental Science and Policy*, 4: 107–116.
- Sheppard SC, Bittman S. 2011. Farm survey used to guide estimates of nitrogen intake and ammonia emissions for beef cattle, including early season grazing and piosphere effects. *Animal Feed Science and Technology*, 166–167: 688–698.
- Sheppard SC, Bittman S. 2012. Farm practices as they affect NH₃ emissions from beef cattle. *Canadian Journal of Animal Science*, 92: 525–543.
- Sheppard SC, Bittman S, Bruulsema TW. 2010a. Monthly ammonia emissions from fertilizers in 12 Canadian ecoregions. *Canadian Journal of Soil Science*, 90: 113–127.
- Sheppard SC, Bittman S, Swift ML, Beaulieu M, Sheppard MI. 2011a. Ecoregion and farm size differences in dairy feed and manure nitrogen management: A survey. *Canadian Journal of Animal Science*, 91: 459–473.
- Sheppard SC, Bittman S, Swift ML, Tait J. 2010b. Farm practices survey and modelling to estimate monthly NH₃ emissions from swine production in 12 Ecoregions of Canada. *Canadian Journal of Animal Science*, 90: 145–158.
- Sheppard SC, Bittman S, Swift ML, Tait J. 2011b. Modelling monthly NH₃ emissions from dairy in 12 ecoregions of Canada. *Canadian Journal of Animal Science*, 91(4): 649–661.
- Sheppard SC, Bittman S, Tait J. 2009. Monthly NH₃ emissions from poultry in 12 Ecoregions of Canada. *Canadian Journal of Animal Science*, 89: 21–35.
- Small JA, McCaughey WP. 1999. Beef cattle management in Manitoba. *Canadian Journal of Animal Science*, 79: 539–544.
- [StatCan] Statistics Canada. 1987. Agriculture, Census Canada 1986. Catalogue No. 96-102.
- [StatCan] Statistics Canada. 1992. Agricultural Profile of Canada in 1991. Census of Agriculture. Catalogue No. 93350.
- [StatCan] Statistics Canada. 1997. Agricultural Profile of Canada in 1996. Census of Agriculture. Catalogue No. 93356.
- [StatCan] Statistics Canada. 2002. Agricultural Profile of Canada in 2001. Census of Agriculture. Catalogue No. 95F0301XIE.
- [StatCan] Statistics Canada. 2007a. 2006 Census of Agriculture [accessed 2015 December 4]. Catalogue No. 95-629. Available online at: <http://www.statcan.gc.ca/ca-ra2006/index-eng.htm>.
- [StatCan] Statistics Canada. 2007b. Selected Historical Data from the Census of Agriculture [accessed 2015 December 4]. Catalogue No. 95-632. Available online at: <http://www.statcan.gc.ca/pub/95-632-x/2007000/4129763-eng.htm>.
- [StatCan] Statistics Canada. 2008. Alternative Livestock on Canadian Farms. Census years 1981, 1986, 1991, 1996, 2001 and 2006. Catalogue No. 23-502-X.
- [StatCan] Statistics Canada. 2012a. Table 95-640-XWE – 2011. Farm and farm operator data (database) [accessed 2015 December 4]. Available online at: <https://www150.statcan.gc.ca/n1/pub/95-640-x/95-640-x2011001-eng.htm>.
- [StatCan] Statistics Canada. 2016. Census Profile [accessed 2019 May 30]. Available online at: <https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang=E>.
- Statistics Canada. No date (a). Table 17-10-0135-01. Population estimates, July 1, by census metropolitan area and census agglomeration, 2016 boundaries [accessed 2019 May 30]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710013501>.
- Statistics Canada. No date (b). Table 32-10-0126-01 (formerly CANSIM 003-0028). Hogs, sheep and lambs, farm and meat production [accessed 2020 September 30]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210012601>.
- Statistics Canada. No date (c). Table 32-10-0129-01 (formerly CANSIM 003-0031). Number of sheep and lambs on farms, annual (head) [accessed 2020 September 30]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210012901>.
- Statistics Canada. No date (d). Table 32-10-0130-01 (formerly: CANSIM 003-0032). Number of cattle, by class and farm type, annual (head) [accessed 2020 September 29]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210013001>.

- Statistics Canada. No date (e). Table 32-10-0145-01 (formerly CANSIM 003-0100). Hogs statistics, number of hogs on farms at end of semi-annual period (head) [accessed 2020 September 30]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=3210014501>.
- Statistics Canada. No date (f). Table 32-10-0290-01 (formerly CANSIM 003-0004). Number of hogs on farms at end of quarter, quarterly (head) [accessed 2017 September 9]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210029001>.
- Statistics Canada. No date (g). Table: 32-10-0359-01. Estimated areas, yield, production, average farm price and total farm value of principal field crops. <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210035901> (accessed 26 Nov. 2021)
- Statistics Canada. No date (h). Table 32-10-0038-01 (formerly CANSIM 001-0068). Fertilizer shipments to Canadian agriculture markets, by nutrient content and fertilizer year, cumulative data (x 1,000) [accessed 2021 November 22]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003901>.
- Statistics Canada. No date (i). Table 32-10-0038-01 (formerly CANSIM 001-0068). Fertilizer shipments to Canadian agriculture and export markets, by product type and fertilizer year, cumulative data (x 1,000) [accessed 2021 November 22]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210003801>.
- [U.S. EPA] United States Environmental Protection Agency. 2004. *National emission inventory—Ammonia emissions from animal husbandry operations*. Draft report. January 30, 2004. Washington (DC): U.S. Environmental Protection Agency.
- VanderZaag AC, Gordon RJ, Jamieson RC, Burton DL, Stratton GW. 2009. Gas emissions from straw covered liquid dairy manure during summer storage and autumn agitation. *Transactions of the ASABE*, 52: 599–608.
- VanderZaag AC, Gordon RJ, Jamieson RC, Burton DL, Stratton GW. 2010. Effects of winter storage conditions and subsequent agitation on gaseous emissions from liquid dairy manure. *Canadian Journal of Soil Science*, 90: 229–239.
- Vanderzaag AC, MacDonald JD, Evans L, Vergé XPC, Desjardins RL. 2013. Towards an inventory of methane emissions from manure management that is responsive to changes on Canadian farms. *Environmental Research Letters*, 8(3).
- VanderZaag AC, Baldé H, Crolla A, Gordon RJ, Ngwabie NM, Wagner-Riddle C, Desjardins R, MacDonald JD. 2018. Potential methane emission reductions for two manure treatment technologies. *Environmental Technology*, 39(7): 851–858.
- Van Haarlem RP, Desjardins RL, Gao Z, Flesch TK, Li X. 2008. Methane and ammonia emissions from a beef feedlot in western Canada for a twelve-day period in the fall. *Canadian Journal of Animal Science*, 88: 641–649.
- Wagner-Riddle C, Furun A, McLaughlin NL, Lee I, Barbeau J, Jayasundara S, Parkin G, von Bertoldi P, Warland J. 2007. Intensive measurement of nitrous oxide emissions from a corn soybean wheat rotation under two contrasting management systems over 5 years. *Global Change Biology*, 13: 1722–1736.
- Wagner-Riddle C, Park KH, Thurtell GW. 2006. A micrometeorological mass balance approach for greenhouse gas flux measurements from stored animal manure. *Agricultural and Forest Meteorology*, 136: 175–187.
- Wagner-Riddle C, Thurtell GW. 1998. Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. *Nutrient Cycling in Agroecosystems*, 52: 151–163.
- Western Canadian Dairy Herd Improvement Services. 2002. 2002 herd improvement report. Edmonton (AB). Canada. 16 pp.
- Weston RH. 2002. Constraints on feed intake by grazing sheep. In: Freer M, Dove H, editors. *Sheep nutrition*. Collingwood (AU): CSIRO Publishing.
- Xu S, Hao X, Stanford K, McAllister T, Larney FJ, Wang J. 2007. Greenhouse gas emissions during co-composting of cattle mortalities with manure. *Nutrient Cycling in Agroecosystems*, 78: 177–187.
- Yang JY, De Jong R, Drury CF, Huffman E, Kirkwood V, Yang XM. 2007. Development of a Canadian agricultural nitrogen model (CANB v2.0): simulation of the nitrogen indicators and integrated modeling for policy scenarios. *Canadian Journal of Soil Science*, 87: 153–165.
- Yang JY, Huffman EC, Drury, CF, Yang XM, De Jong R. 2011. Estimating the impact of manure nitrogen losses on total nitrogen application on agricultural land in Canada. *Canadian Journal of Soil Science*, 91(1): 107–122.
- ZebARTH BJ, Hii B, Liebscher H, Chipperfield K, Paul JW, Grove G, Szeto SY. 1998. Agricultural land use practices and nitrate contamination in the Abbotsford aquifer, British Columbia, Canada. *Agriculture, Ecosystems & Environment*, 69: 99–112.

Annex 3.5, Methodology for Land Use, Land-Use Change and Forestry

- Agriculture and Agri-Food Canada. 2021. Agriculture and Agri-Food Canada semi-decadal land use time series. Available online at <https://open.canada.ca/data/en/dataset/fa84a70f-03ad-4946-b0f8-a3b481dd5248>
- Aoyama M, Angers DA, N'dayegamiye A, Bissonnette N. 1999. Protected organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications. *Canadian Journal of Soil Science* 79: 419–425.
- Bailey AW, Liang BC. 2013. *Burning of managed grasslands in Alberta, Saskatchewan and British Columbia*. Western Rangeland Consultants Inc., Edmonton (AB); Pollutant Inventories and Reporting Division, Environment Canada, Gatineau (QC).
- Baron VS, Mapfumo E, Dick AC, Naeth MA, Okine EK, Chanasyk DS. 2002. Grazing intensity impacts on pasture carbon and nitrogen flow. *Journal of Range Management* 55(6): 535–541.
- Bartelink HH. 1998. A model of dry matter partitioning in trees. *Tree Physiology* 18(2): 91–101.
- Bhandral R, Bittman S, Kowalenko G, Buckley K, Chantigny MH, Hunt DE, Bounaix F, Friesen A. 2009. Enhancing soil infiltration reduces gaseous emissions and improves N uptake from applied dairy slurry. *Journal of Environmental Quality* 38: 1372–1382.

- Biederbeck VO, Campbell CA, Zentner RP. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. *Canadian Journal of Soil Science* 64: 355–367.
- Biondini ME, Manske L. 1996. Grazing frequency and ecosystem processes in a northern mixed prairie, USA. *Ecological Applications* 6(1): 239–256.
- Blain D, Seed E, Lindsay M, Hayne S, McGovern M. 2014. *Forest land and other land conversion to wetlands (reservoirs) estimation and reporting of CO₂ emissions*. Unpublished report. Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- Blondel A, Tracey K. 2018. *Table of estimated densities of wood used for residential heating - per reconciliation unit*. Unpublished file. Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- Bolinder MA. 2004. *Contribution aux connaissances de la dynamique du C dans les systèmes sol-plante de l'est du Canada*. PhD thesis, Université Laval, Sainte-Foy (QC).
- Bolinder MA, Janzen HH, Gregorich EG, Angers DA, VandenBygaart AJ. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems and Environment* 118: 29–42.
- Boudewyn P, Song X, Magnussen S, Gillis M. 2007. *Model-based, volume-to-biomass conversion for forested and vegetated land in Canada*. Natural Resources Canada, Canadian Forest Service. Information Report – BC-X-411.
- Bowman DMJS, Williamson GJ, Abatzoglou JT, Kolden CA, Cochrane MA, Smith AMS. 2017. Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology and Evolution* 1: 0058.
- Bremer E, Janzen HH, Johnston AM. 1994. Sensitivity of total, light fraction and mineralizable organic matter to management practices in a Lethbridge soil. *Canadian Journal of Soil Science* 74: 131–138.
- Briggs D. 1994. Forest Products Measurements and Conversion Factors: with Special Emphasis on the U.S. Pacific Northwest. College of Forest Resources, University of Washington, Seattle. Available online at: http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_book.asp.
- Bruce JP, Frome M, Hautes E, Janzen H, Lal R, Paustian K. 1999. Carbon sequestration in soils. *Journal of Soil Water Conservation* 54: 382–389.
- Campbell CA, Janzen HH, Paustian K, Gregorich EG, Sherrod L, Liang BC, Zentner RP. 2005. Carbon storage in soils of the North American Great Plains: Effect of cropping frequency. *Agronomy Journal* 97: 349–363.
- Campbell CA, McConkey BG, Zentner RP, Dyck RP, Selles F, Curtin D. 1995. Carbon sequestration in a Brown Chernozem as affected by tillage and rotation. *Canadian Journal of Soil Science* 75: 449–458.
- Campbell CA, McConkey BG, Zentner RP, Selles F, Curtin D. 1996a. Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. *Canadian Journal of Soil Science* 76: 395–401.
- Campbell CA, McConkey BG, Zentner RP, Selles F, Curtin D. 1996b. Tillage and crop rotation effects on soil organic matter in a coarse-textured Typic Haploboroll in southwestern Saskatchewan. *Soil & Tillage Research* 37: 3–14.
- Campbell CA, Selles F, LaFond GP, McConkey BG, Hahn D. 1998. Effect of crop management on C and N in long-term crop rotations after adopting no-tillage management: Comparison of soil sampling strategies. *Canadian Journal of Soil Science* 78: 155–162.
- Campbell CA, Zentner RP, Liang BC, Roloff G, Gregorich EG, Blomert B. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan—Effect of crop rotations and fertilizers. *Canadian Journal of Soil Science* 80: 179–192.
- Canadian Facts. 1997. *Residential Fuelwood Combustion in Canada*. Canadian Facts. Prepared for the National Emission Inventory and Project Task Group. Toronto (ON): CF Group Inc.
- Carter MR, Kunelius HT, Sanderson JB, Kimpinski J, Platt HW, Bolinder MA. 2003. Trends in productivity parameters and soil health under long-term two-year potato rotations. *Soil & Tillage Research (Special issue)* 72: 153–168.
- Cerkowniak D. 2019. *National Inventory Report – 2020: Results, methodological changes and updates to LULUCF reporting for agriculture*. Report submitted to the Pollutant Inventories and Reporting Division, Environment Canada, by the Research Branch of Agriculture and Agri-Food Canada, Saskatoon (SK).
- Chantigny MH, Angers DA, Beauchamp CJ. 2000. Decomposition of de-inking paper sludge in agricultural soils as characterized by carbohydrate analysis. *Soil Biology and Biochemistry* 32: 1561–1570.
- Chantigny MH, Angers DA, Rochette P, Bélanger G, Massé D, Côté D. 2007. Gaseous nitrogen emissions and forage nitrogen uptake on soils fertilized with raw and treated swine manure. *Journal of Environmental Quality* 36: 1864–1872.
- Chantigny MH, Rochette P, Angers DA, Bittman S, Buckley K, Massé D, Bélanger G, Eriksen-Hamel N, Gasser M. 2010. Soil nitrous oxide emissions following band-incorporation of fertilizer nitrogen and swine manure. *Journal of Environmental Quality* 39: 1545–1553.
- Chantigny MH, Royer I, Rochette P, Angers DA, Massé DI, Benchaar C. 2012. Manure storage strategies altered nutrient availability and greenhouse gas emissions following application to soils. 3rd AQSSS-CSSS Joint Meeting/Congrès conjoint AQSSS-SCSS: Soils in a changing climate: Friend or foe?, Manoir St-Castin, Québec City, QC, Canada, June 3–8, 2012.
- Cleary J. 2003. *Greenhouse gas emissions from peat extraction in Canada: A life cycle perspective*. MSc thesis, McGill University, Montreal (QC). C2GCR Report No. 2003-1.
- Cleary J, Roulet N, Moore T. 2005. Greenhouse gas emissions from Canadian peat extraction, 1990–2000: A life-cycle analysis. *Ambio* 34: 456–461.

- Cofer WR, Winstead EL, Stocks BJ, Goldammer JG, Cahoon DR. 1998. Crown fire emissions of CO₂, CO, H₂, CO₄, and TNMHC from a dense jack pine boreal forest fire. *Geophysical Research Letters* 25: 3919–3922.
- Danneyrolles V, Cyr D, Girardin MP, Gauthier S, Asselin H, Bergeron Y. 2021. Influences of climate fluctuations on northeastern North America's burned areas largely outweigh those of European settlement since AD 1850. *Environmental Research Letters* 16: 114007.
- Doyon F, Parcerisas L., Senécal J-F, Trégaro R, Cordero R., Mina M. 2019. *Évaluation de l'effet de l'extraction de bois de chauffage résidentiel sur le bilan de carbone des forêts canadiennes*. Unpublished report. Submitted to Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- Duchemin É. 2002. Canadian Reservoir Database / Répertoire des réservoirs canadiens [computer file]. Environment Canada and DREXenvironment (distributor).
- Duchemin É. 2006. *Émissions de gaz provoquant l'effet de serre à partir des terres inondées au Canada*. Final report submitted to the Greenhouse Gas Division, Environment Canada.
- Dyk A, Leckie D, Tinis S, Ortlepp S. 2015. *Canada's National Deforestation Monitoring System: System description*. Natural Resources Canada, Canadian Forest Service. 30 pp. Report BC-X-439.
- Eichel F. 2006. *Review of Environment Canada reservoir flooding dates on hydro reservoirs for NIR 2007*. Canadian Forest Service, Natural Resources Canada. 6 pp.
- Ellert B, Bettany JR. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science* 75: 529–538.
- [FAO] Food and Agriculture Organization. 2010. Forest Product Conversion Factors for the UNECE Region. Geneva Timber and Forest Discussion Paper 49. Food and Agricultural Organization of the United Nations.
- Fan J, McConkey BG, Janzen HH, Townley-Smith L, Wang H. 2017. Harvest index–yield relationship for estimating crop residue in cold continental climates. *Field Crop Research* 204: 153–157.
- Forge T, Kenney E, Hashimoto N, Neilsen D, ZebARTH B. 2016. Compost and poultry manure as preplant soil amendments for red raspberry: Comparative effects on root lesion nematodes, soil quality and risk of nitrate leaching. *Agriculture, Ecosystem and Environment* 223: 48–58.
- Gaboriau DM, Remy CC, Girardin MP, Asselin H, Hély C, Bergeron Y, Ali AA. 2020. Temperature and fuel availability control fire size/severity in the boreal forest of central Northwest Territories, Canada. *Quaternary Science Reviews* 250: 106697.
- Garcia Bravo T. 2015. *Picea mariana (Mill.) B.S.P plantation on cutover peatland in Alberta (Canada): Evaluating the effect of fertilization and resulting carbon stocks*. MSc Thesis. University of Calgary. Calgary (AB), 103 pp.
- Gillies, C. 2016. *A review of forestry management practices on peatlands in Canada*. Unpublished report. FPInnovations. 41 pp.
- Glatzel S, Kalbitz K, Dalva M, Moore T. 2003. Dissolved organic matter properties and their relationship to carbon dioxide efflux from restored peat bogs. *Geoderma* 113: 397–411.
- González E, Rochefort L. 2014. Drivers of success in 53 cutover bogs restored by a moss layer transfer technique. *Ecological Engineering* 68: 279–290.
- Gould WA, Raynolds M, Walker DA. 2003. Vegetation, plant biomass, and net primary productivity patterns in the Canadian Arctic. *Journal of Geophysical Research: Atmospheres* 108(D2). doi: <http://dx.doi.org/10.1029/2001JD000948>.
- Gouvernement du Québec, 2018. Statistiques forestières. Ministère des Forêts, Faune et Parcs Québec. Available online at: <https://mffp.gouv.qc.ca/les-forêts/connaissances/statistiques-forestieres>.
- Grant RF, Juma NG, Robertson JA, Izaurrealde RC, McGill WB. 2001. Long-Term Changes in Soil Carbon under Different Fertilizer, Manure, and Rotation. *Soil Science Society American Journal* 65: 205–214. <https://doi.org/https://doi.org/10.2136/sssaj2001.651205x>
- Hafer M, Hudson B, Voicu M, Magnan M, Magnus G, Metsaranta J, Kurz W. 2020. *NFCMARS Updates National Forest GHG Inventory Reporting (NIR 2021)*. Natural Resources Canada, Canadian Forest Service, Unpublished File Report.
- Hanes CC, Wang X, Jain P, Parisien M-A, Little JM, Flannigan MD. 2019. Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research* 49: 256–269.
- Hao X, Chang C, Travis GR, Zhang F. 2003. Soil carbon and nitrogen response to 25 annual cattle manure applications. *Journal of Plant Nutrient and Soil Science* 166: 239–245.
- Hayne S, Jenkins C, Garneau M. 2014. *Off-site GHG emissions from Canadian peat products*. Unpublished report. Pollutant Inventories and Reporting Division, Environment Canada.
- Hayne S, Verbicki M. 2011. *Aboveground biomass density of Canadian peatlands*. Unpublished report. Pollutant Inventories and Reporting Division, Environment Canada.
- Hermosilla T, Wulder M, White J, Coops N, Hobart G, Campbell L. 2016. Mass data processing of time series Landsat imagery: pixels to data products for forest monitoring. *International Journal of Digital Earth*. doi: <http://dx.doi.org/10.1080/17538947.2016.1187673>.
- Holden ZA, Swanson A, Luce CH, Jolly WM, Maneta M, Oyler JW, Warren DA, Parsons R, Affleck D. 2018. Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences* 115: E8349–E8357.

- Hudson JM, Henry GH. 2009. Increased plant biomass in a High Arctic heath community from 1981 to 2008. *Ecology* 90(10): 2657–2663.
- Huffman T, Leckie D, McGovern M, Olesen M, Green M, Hill DA, Rounce T, Churchill J, Liu J. 2015a. Integration of multiple spatial datasets in the development of a temporal series of high-accuracy, high-resolution land use maps. Proceedings of the 35th EARSeL Symposium, Stockholm, Sweden, June 15–19, 2015.
- Huffman T, Liu J, McGovern M, McConkey B, Martin T. 2015b. Carbon stock and change from woody biomass on Canada's cropland between 1990 and 2000. *Agriculture, Ecosystems & Environment* 205: 102–111. doi: <http://dx.doi.org/10.1016/j.agee.2014.10.009>.
- Hillman G. 1987. *Improving wetlands for forestry in Canada (Information Report NOR-X-288)*. Edmonton, AB: Canadian Forest Service – Northern Forestry Centre.
- [IPCC] Intergovernmental Panel on Climate Change. 2003. *Good practice guidance for land use, land-use change and forestry*. IPCC National Greenhouse Gas Inventories Programme. Available online at: <https://www.ipcc-nccc.iges.or.jp/public/gpglulucf/gpglulucf.html>.
- [IPCC] Intergovernmental Panel on Climate Change. 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4, Agriculture, Forestry, and Other Land Use, Chapter 5 – Cropland. Calvo Buendia, E., K. Tanabe, A. Kranjc, J. Baasansuren, M. Fukuda, S. Ngarize, A. Osako, Y. Pyrozenko, P. Shermanau, and S. Federici (eds). IPCC, Switzerland.
- [IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC guidelines for national greenhouse gas inventories, Volume 4: Agriculture, forestry and other land use*. IPCC National Greenhouse Gas Inventories Programme. Available online at: <https://www.ipcc-nccc.iges.or.jp/public/2006gl/vol4.html>.
- [IPCC] Intergovernmental Panel on Climate Change. 2010. *Revisiting the use of managed land as a proxy for estimating national anthropogenic emissions and removals*. Eggleston HS, Srivastava N, Tanabe K, Baasansuren J, editors. IGES, Japan, IPCC Expert Meeting Report.
- [IPCC] Intergovernmental Panel on Climate Change. 2014. *2013 Supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands*. Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M, Troxler TG, editors. IPCC, Switzerland. Available online at: <http://www.ipcc-nccc.iges.or.jp/public/wetlands/>.
- Izaurrealde RC, McGill WB, Robertson JA, Juma NG, Thurston JJ. 2001. Carbon balance of the Breton classical plots over half a century. *Soil Science Society American Journal* 65: 431–441.
- Janzen HH, Campbell CA, Gregorich EG, Ellert BH. 1997. *Soil carbon dynamics in Canadian agroecosystems*. In: Lal R, Kimble JM, Follett RF, Stewart BA, editors. *Soil processes and the carbon cycle*. Boca Raton (FL): CRC Press. p. 57–80.
- Janzen HH, Campbell CA, Izaurrealde RC, Ellert BH, Juma N, McGill WB, Zentner RP. 1998. Management effects on soil C storage in the Canadian prairies. *Soil & Tillage Research* 47: 181–195.
- Janzen HH, Beauchemin KA, Bruinsma Y, Campbell CA, Desjardins RL, Ellert BH, Smith EG. 2003. The fate of nitrogen in agroecosystems: an illustration using Canadian estimates. *Nutrient Cycling in Agroecosystem* 67: 85–102.
- Kasischke ES, Bruhwiler LP. 2003. Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998. *Journal of Geophysical Research Atmospheres* 108(D1): 8146.
- Kelley DI, Bistinas I, Whitley R, Burton C, Marthews TR, Dong N. 2019. How contemporary bioclimatic and human controls change global fire regimes. *Nature Climate Change* 9: 690–6.
- Kurz WA, Apps MJ, Webb TM, McNamee PJ. 1992. *The carbon budget of the Canadian forest sector: Phase 1*. Edmonton (AB): Northern Forestry Centre, Forestry Canada. Information Report NOR-X-326.
- Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET, Carroll AL, Ebata T, Safranyik L. 2008a. Mountain pine beetle and forest carbon feedback to climate change. *Nature* 452: 987–990.
- Kurz WA, Dymond CC, White TM, Stinson G, Shaw CH, Rampley GJ, Smyth C, Simpson BN, Neilson ET, Trofymow JA, et al. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* 220: 480–504.
- Kurz WA, Hayne S, Fellows M, MacDonald JD, Metsaranta JM, Hafer M, Blain D. 2018. Quantifying the impacts of human activities on reported greenhouse gas emissions and removals in Canada's managed forest: conceptual framework and implementation. *Canadian Journal of Forest Research*. Available online at: <http://www.nrcresearchpress.com/doi/full/10.1139/cjfr-2018-0176>.
- Kurz WA, Stinson G, Rampley GJ, Dymond CC, Neilson ET. 2008b. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences* 105: 1551–1555.
- Kurz WA, Shaw CH, Boisvenue C, Stinson G, Metsaranta J, Leckie D, Dyk A, Smyth C, Neilson ET. 2013. Carbon in Canada's boreal forest – A synthesis. *Environmental Reviews* 21: 260–292.
- Larney FJ, Janzen HH. 1996. Restoration of productivity to a desurfaced soil with livestock manure, crop residue, and fertilizer amendments. *Agronomy Journal* 88: 921–927.
- Leckie D. 2006a. *Deforestation monitoring pilot project reports v 1.0*. Canadian Forest Service, Natural Resources Canada. 199 pp. Report DRS-Q-004.
- Leckie D. 2006b. *NIR 2006 Records of decision for Canada's national deforestation estimate 2006*. Canadian Forest Service, Natural Resources Canada. 56 pp. Report DRS-N-011.
- Leckie D. 2011. *Deforestation area estimation uncertainty for Canada's national inventory report greenhouse gas sources and sinks 2011*. Canadian Forest Service, Natural Resources Canada. 12 pp. Report DRS-N-030.

- Leckie D, Paradine D, Burt W, Hardman D, Tinis S. 2006. *NIR 2006 Deforestation Area Estimation for Canada: Methods Summary*. Victoria (BC): Canadian Forest Service, Natural Resources Canada. 13 pp. Report DRS-Q-001.
- Leckie D, Dyk A, Ortlepp S, Tinis S. 2010a. *Records of decision for Canada's national deforestation estimate*. Canadian Forest Service, Natural Resources Canada. 20 pp. Report DRS-N-029.
- Leckie D, Dyk A, Paradine D, Tammadge D, Tinis S. 2010b. *Deforestation interpretation guide (Version NIR 2011)*. Canadian Forest Service, Natural Resources Canada. 85 pp. Report DRS-M-016.
- Leckie D, Paradine D, Kurz W, Magnussen S. 2015. Deforestation mapping sampling designs for Canadian landscapes. *Canadian Journal of Forestry Research* 45: 1564–1576.
- Leckie DG, Gillis MD, Wulder MA. 2002. Deforestation estimation for Canada under the Kyoto Protocol: A design study. *Canadian Journal of Remote Sensing* 28(5): 672–678.
- Li Z, Kurz WA, Apps MJ, Beukema SJ. 2003. Belowground biomass dynamics in the Carbon Budget Model of the Canadian Forest Sector: recent improvements and implications for the estimation of NPP and NEP. *Canadian Journal of Forest Research* 33:126–136.
- Liang BC, VandenBygaart AJ, Cerkowniak C, MacDonald DJ, McConkey BG, Desjardins RL, Angers D.A. 2020a. Revisiting no no-till's impact on soil organic carbon storage in Canada. *Soil & Tillage Research* 198, 104529
- Liang BC, MacDonald DJ, Thiagarajan C, Flemming C, Cerkowniak D, Desjardins R. 2020b. Developing a country specific method for estimating nitrous oxide emissions from agricultural soils in Canada. *Nutrient Cycling in Agroecosystem* 117:145–167
- Liang BC, Hao XY, Schoenau J, Ma BL, Zhang TQ, MacDonald JD, Chantigny M, Dyck M, Smith WN, Malhi S.S., Thiagarajan A, Lafond J, Angers DA. 2021. Manure-induced carbon retention measured from long-term field studies in Canada. *Agriculture, Ecosystems and Environment* 321: 107619
- Liang BC, Campbell CA, McConkey BG, Padbury B, Collas P. 2005. An empirical model for estimating carbon sequestration on the Canadian prairies. *Canadian Journal of Soil Science* 85: 549–556.
- Liang BC, Gregorich EG, MacKenzie AF. 1996. Modelling the effects of inorganic and organic amendments on organic matter in a Quebec soil. *Soil Science* 161: 109–114.
- Liang BC, Padbury G, Patterson G. 2004. *Cultivated organic soils in Canada*. Gatineau (QC): Greenhouse Gas Division, Environment Canada.
- Liebig MA, Morgan JA, Reeder JD, Ellert BH, Gollany HT, Schuman GE. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil & Tillage Research* 83(1): 25–52.
- Litton CM, Ryan MG, Tinker DB, Knight DH. 2003. Belowground and aboveground biomass in young postfire lodgepole pine forests of contrasting tree density. *Canadian Journal of Forest Research* 33(2): 351–363.
- Lynch DH, Voroney RP, Warman PR. 2005. Soil physical properties and organic matter fractions under forages receiving composts, manure or fertilizer. *Compost Science and Utilization* 13: 252–261.
- Magnuson JL, Robertson DM, Benson BJ, Wynne RH, Livingstone DM, Arai T, Assel TA, Barry RG, Card V, Kuusisto E, et al. 2000. Historical trends in lake and river ice cover in the northern hemisphere. *Science* 289: 1743–1746.
- Maillard É, Angers DA, Chantigny M, Lafond J, Pageau D, Rochette P, Lévesque G, Leclerc ML, Parent LÉ. 2016. Greater accumulation of soil organic carbon after liquid dairy manure application under cereal-forage rotation than cereal monoculture. *Agriculture, Ecosystems and Environment* 233: 171–178.
- Maillard E, Angers DA, Chantigny M, Bittman S, Rochette P, Lévesque G, Hunt D, Parent LE. 2015. Carbon accumulates in organo-mineral complexes after long-term liquid dairy manure application. *Agriculture, Ecosystems and Environment* 202: 108–119.
- Mailvaganam S. 2002. 2001 Ontario Grape Vine Survey. Ontario Ministry of Agriculture and Food. Available on request from stats. omafra@ontario.ca.
- Marshall IB, Schut PH, Ballard M. 1999. *A National Ecological Framework for Canada: Attribute Data*. Prepared by Environment Canada and Agriculture and Agri-Food Canada. Available online at: <http://sis.agr.gc.ca/cansis/nsdb/ecostrat/1999report/index.html>.
- McConkey B, Angers D, Bentham M, Boehm M, Brierley T, Cerkowniak D, Liang BC, Collas P, de Gooijer H, Desjardins R, et al. 2007a. *CanAG-MARS methodology and greenhouse gas estimates for agricultural land in the LULUCF sector for NIR 2006*. Report submitted to the Greenhouse Gas Division, Environment Canada, by the Research Branch of Agriculture and Agri-Food Canada.
- McConkey BG, Liang BC, Campbell CA, Curtin D, Moulin A, Brandt SA, Lafond GP. 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. *Soil & Tillage Research* 74: 81–90.
- McConkey BG, VandenBygaart B, Hutchinson J, Huffman T, Martin T. 2007b. *Uncertainty analysis for carbon change—cropland remaining cropland*. Report submitted to Environment Canada by the Research Branch of Agriculture and Agri-Food Canada.
- McCrae T, Smith CAS, Gregorich LJ. 2000. *Environmental sustainability of Canadian agriculture: Report of the Agri-Environmental Indicator Project*. Ottawa (ON): Agriculture and Agri-Food Canada. Publication 2022/E.
- McGovern M. 2014. *GHG spatial reporting structure for Canada's land use, land-use change and forestry sector – Reporting zones and reconciliation units*. Pollutant Inventory and Reporting Division, Environment Canada.
- McGovern M, Pasher J. 2016. Canadian urban tree canopy cover and carbon sequestration status and change 1990–2012. *Urban Forestry & Urban Greening* 20: 227–232.
- McGovern M, Pasher J, Laurin E. 2016. *NORDIS: Digitization of human disturbance activity in Canada's North for 1990, 2000 and 2010*. Report of the Wildlife Landscape Science and Technology Division. Ottawa (ON). Environment and Climate Change Canada.

- McKenney DW, Hutchinson MF, Kesteven JL, Vernier LA. 2001. Canada's plant hardiness zones revisited using modern climate interpolation techniques. *Canadian Journal of Plant Science* 81: 129–143.
- McNeil P., Waddington JM. 2003. Moisture controls on Sphagnum growth and CO₂ exchange on a cutover bog. *Journal of Applied Ecology*, 40(2): 354–367.
- Metsaranta J, Morken S, Hafer M. 2014. *Uncertainty estimates: National forest GHG inventory reporting for the 2014 National Inventory Report*. Unpublished manuscript.
- Metsaranta J, Magnan M, Xie S, Hafer M, Morken S. 2020. *Uncertainty estimates: National forest GHG inventory reporting (NIR 2021), including Harvested Wood Products*. Unpublished manuscript.
- MDA-Federal. 2004. Landsat Geocover 1990/TM edition mosaic. ETM-EarthSat-MrSID, 1.0, USGS, Sioux Falls, South Dakota.
- Metsaranta JM, Shaw CH, Kurz WA, Boisvenue C, Morken S. 2017. Uncertainty of inventory-based estimates of the carbon dynamics of Canada's managed forest (1990–2014). *Canadian Journal of Forest Research* 47(8): 1082–1094.
- Monreal CM, Zentner RP, Robertson JA. 1997. An analysis of soil organic matter dynamics in relation to management, erosion and yield of wheat in long-term crop rotation plots. *Canadian Journal of Soil Science* 77: 553–563.
- [NRCan] Natural Resources Canada. 1974. Lakes – Ice Free Period [map], 1:35,000,000. In: National atlas of Canada, 4th ed. Available online at: <http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/5c2581ff-1c35-5310-b31a-7960ca892d0b.html>.
- [NRCan] Natural Resources Canada. 2020. *Preliminary estimates of mineral production of Canada, by Province, 2020*. Natural Resources Canada. Available online at: <https://mmsd.nrcan-rncan.gc.ca/prod-prod/ann-ann-eng.aspx?FileT=2020&Lang=en>.
- Nendel C, Kersebaum KC. 2004. A simple model approach to simulate nitrogen dynamics in vineyard soils. *Ecological Modelling* 177: 1–5.
- Nowak DJ, Greenfield EJ, Hoehn RE, Lapoint E. 2013. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environmental Pollution* 178: 229–236.
- Ogle SM, Swan A, Paustian K. 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture, Ecosystems and Environment* 149: 37–49.
- Paré T, Dinel H, Moulin AP, Townley-Smith L. 1999. Organic matter quality and structural stability of a Black Chernozemic soil under different manure and tillage practices. *Geoderma* 91: 311–326.
- Parton WJ, Schimel DS, Cole CV, Ojima DS. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal* 51: 1173–1179.
- Parton WJ, Stewart JWB, Cole CV. 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry* 5: 109–131.
- Pasher J, McGovern M, Khoury M, Duffe J. 2014. Assessing carbon storage and sequestration by Canada's urban forest using high resolution earth observation data. *Urban Forestry & Urban Greening* 13(3): 484–494.
- Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK. 2002. Change in soil carbon following afforestation. *Forest Ecology and Management* 168(1–3): 241–257.
- Pelster DE, Chantigny MH, Rochette P, Angers DA, Rieux C, Vanasse A. 2012. Nitrous oxide emissions respond differently to mineral and organic nitrogen sources in contrasting soil types. *Journal of Environmental Quality* 41: 427–435.
- Pennock DJ, Frick AH. 2001. The role of field studies in landscape-scale applications of process models: an example of soil redistribution and soil organic carbon modeling using CENTURY. *Soil & Tillage Research* 58(3/4): 183–191.
- Petrone RM, Waddington JM, Price JS. 2001. Ecosystem scale evapotranspiration and net CO₂ exchange from a restored peatland. *Hydrological Processes* 15: 2839–2845.
- Petrone RM, Waddington JM, Price JS. 2003. Ecosystem-scale flux of CO₂ from a restored vacuum harvested peatland. *Wetlands Ecology and Management* 11: 419–432.
- Poulin M, Rochefort L, Quinty F, Lavoie C. 2005. Spontaneous revegetation of mined peatlands in eastern Canada. *Canadian Journal of Botany* 83: 539–557.
- Rees HW, Chow TL, ZebARTH B, Xing Z, Toner P, Lavoie J, Daigle JL. 2014. Impact of supplemental poultry manure application on potato yield and soil properties on a loam soil in north-western New Brunswick. *Canadian Journal of Soil Science* 94: 49–65.
- Rochefort L, Quinty F, Campeau S, Johnson K, Malterer T. 2003. North American approach to the restoration of Sphagnum dominated peatlands. *Wetlands Ecology and Management* 11: 3–20.
- Rochette P, Angers DA, Chantigny MH, Gagnon B, Bertrand N. 2008. N₂O fluxes in soils of contrasting textures fertilized with liquid and solid dairy cattle manures. *Canadian Journal of Soil Science* 88: 175–187.
- Saarnio S, Morero M, Shurpali N, Tuittila E, Makila M, Alm J. 2007. Annual CO₂ and CH₄ fluxes of pristine boreal mires as a background for the lifecycle analyses of peat energy. *Boreal Environmental Research* 12(2): 101–113.
- Schuman GE, Janzen HH, Herrick JE. 2002. Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution* 116: 391–396.
- Shaver GR, Chapin FS. 1991. Production: Biomass relationships and element cycling in contrasting arctic vegetation types. *Ecological Monographs* 61(1): 1–31. doi: <http://dx.doi.org/10.2307/1942997>.
- Skog KE. 2008. Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal* 58: 56–72.
- Smith WN, Rochette P, Monreal C, Desjardins RL, Pattey E, Jaques A. 1997. The rate of carbon change in agricultural soils in Canada at the landscape level. *Canadian Journal of Soil Science* 77: 219–229.

- Smith WN, Desjardins RL, Pattey E. 2000. The net flux of carbon from agricultural soils in Canada 1970–2010. *Global Change Biology* 6(5): 558–568.
- Smith WN, Desjardins RL, Grant B. 2001. Estimated changes in soil carbon associated with agricultural practices in Canada. *Canadian Journal of Soil Science* 81: 221–227.
- Smoliak S. 1965. Effects of manure, straw and inorganic fertilizers on Northern Great Plains ranges. *Journal of Range Management* 18: 11–14.
- Sommerfeldt TG, Chang C, Entz T. 1988. Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. *Soil Science Society American Journal* 52: 1668–1672.
- Statistics Canada. 1997. *Survey on Household Energy Use*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=7737>.
- Statistics Canada. 2003. *Survey on Household Energy Use*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=22916>.
- Statistics Canada 2007. *Households and the Environment Survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=44902>.
- Statistics Canada. 2010. *Introducing a new concept and methodology for delineating settlement boundaries: a research project on Canadian settlements*. Technical Paper. [accessed 2016 Nov 4] Available online at: <http://www.statcan.gc.ca/pub/16-001-m/16-001-m2010011-eng.htm>.
- Statistics Canada. 2011 Census Profile. 2011. Available online at: <http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/index.cfm?Lang=E>. [accessed 2019 Dec 2]
- Statistics Canada 2015. *Households and the Environment Survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=247867>.
- Statistics Canada 2017. *Households and the Environment Survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=433427>.
- Statistics Canada 2019. *Households and the Environment Survey*. Available online at: <https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=3881>.
- Statistics Canada. 2020. Table: 32-10-0359-01 (formerly CANSIM 001-0017). Estimated areas, yield, production, average farm price and total farm value of principal field crops. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210035901> (accessed 26 Nov. 2021)
- Steenberg J, Ristow M, Duinker P, MacDonald D, Samson C, Flemming C. 2021. *An updated approach for assessing Canada's urban forest carbon storage and sequestration*. Internal report. Ottawa (ON): Environment Canada.
- Stinson G, Kurz WA, Smyth CE, Neilson ET, Dymond CC, Metsaranta JM, Boisvenue C, Rampley GJ, Li Q, White TM, Blain D. 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. *Global Change Biology* 17(6): 2227–2244.
- Stocks BJ, Mason JA, Todd JB, Bosch EM, Wotton BM, Amiro BD, Flannigan MD, Hirsch KG, Logan KA, Martell DL, Skinner WR. 2002. Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research: Atmospheres* 107:FFR 5-1-FFR 5-12.
- Strack M, Zuback Y. 2013. Annual carbon balance of a peatland 10 yr following restoration. *Biogeosciences* 10: 2885–2896.
- Strack M, Keith A, Xu B. 2014. Growing season carbon dioxide and methane exchange at a restored peatland on the Western Boreal Plain. *Ecological Engineering* 64: 231–239.
- Tarnocai C. 1997. *The amount of organic carbon in various soil orders and ecological provinces in Canada*. In: Lal R, Kimble JM, Follett RF, Stewart BA, editors. *Soil processes and the carbon cycle*. Boca Raton (FL): CRC Press. p. 81–92.
- Thiagarajan A, Liang BC, MacDonald JD, Smith W, VandenBygaart B, Grant B, Kroebel R, Janzen H, Zhang TQ, McConkey BG, Ma BL, Bremer E, Yang XM, Cerkowniak D, Fan JL. 2021. Challenges in the use of models to estimate the influence of crop residue input on soil organic carbon in long-term experiments (Manuscript in preparation).
- [TNS] TNS Canadian Facts. 2006. *Residential fuelwood combustion in Canada*. Presented to Environment Canada. Report C1077/BT. Toronto (ON): TNS Global.
- [TNS] TNS Canada. 2012. *Residential fuelwood combustion in Canada*. Presented to Natural Resources Canada. Report 1381/BT. Toronto (ON): TNS Canada.
- Tree Canada 2018. *National Urban Forest Trends Report 2018*. Final report submitted to Pollutant Inventory and Reporting Division, Environment and Climate Change Canada.
- Tree Canada 2019. *Urban Forest Biomass Fate Survey 2019*. Final report submitted to Pollutant Inventory and Reporting Division, Environment and Climate Change Canada.
- Trégaro R, Blondel A. 2019. *Analyse de la consommation du bois de chauffage au Canada - Basée sur l'Enquête sur les ménages et l'environnement de 2017 par Statistique Canada*. Final report. Pollutant Inventory and Reporting Division, Environment and Climate Change Canada. Internal document.
- Trégaro R. 2020. *Rapport sur la méthodologie liée aux objectifs de récoltes du bois de chauffage résidentiel*. Final report submitted to Pollutant Inventory and Reporting Division, Environment and Climate Change Canada.
- [U.S. EPA] United States Environmental Protection Agency. 2013. *Inventories of U.S. greenhouse gas emissions and sinks: 1990–2010*. EPA Report 430-R-12-001.

- VandenBygaart AJ, Gregorich EG, Angers DA. 2003. Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies. *Canadian Journal of Soil Science* 83: 363–380.
- VandenBygaart AJ, McConkey BG, Angers DA, Smith W, De Gooijer H, Bentham M, Martin T. 2008. Soil carbon change factors for the Canadian agriculture national greenhouse gas inventory. *Canadian Journal of Soil Science* 88: 671–680.
- Voroney RP, Angers DA. 1995. *Analysis of the short-term effects of management on soil organic matter using the CENTURY model*. In: Lal R, Kimble J, Levine E and Stewart BA, editors. *Soil management and greenhouse effect*. New York (NY): Springer-Verlag. p. 113–120.
- Waddington JM, Day SM. 2007. Methane emissions from a peatland following restoration. *Journal of Geophysical Research* 112: 1–11.
- Waddington JM, Price JS. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography* 21(5): 433–451.
- Waddington JM, Strack M, Greenwood MJ. 2010. Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO₂ exchange to ecosystem-scale restoration. *Journal of Geophysical Research* 115: 1–13.
- Waddington JM, Toth K, Bourbonniere R. 2008. Dissolved organic carbon export from a cutover and restored peatland. *Hydrological Processes* 22: 2215–2224.
- Waddington JM, Warner KD. 2001. Atmospheric CO₂ sequestration in restored mined peatlands. *Ecoscience* 8(3): 359–368.
- Waddington JM, Warner KD, Kennedy GW. 2002. Cutover peatlands: A persistent source of atmospheric CO₂. *Global Biogeochemical Cycles* 16: 1–7.
- Wang X, Parisien M-A, Taylor SW, Candau J-N, Stralberg D, Marshall GA, Little JM, Flannigan MD. 2017. Projected changes in daily fire spread across Canada over the next century. *Environmental Research Letters* 12: 025005.
- White T, Kurz WA. 2005. Afforestation on private land in Canada from 1990 to 2002 estimated from historical records. *The Forestry Chronicle* 81(4): 491–497.
- White T, Luckai N, Larocque GR, Kurz WA, Smyth C. 2008. A practical approach for assessing the sensitivity of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). *Ecological Modelling* 219(3–4): 373–382.
- Woods M, Robinson D. 2007. Development of FVS Ontario: A Forest Vegetation Simulator Variant and Application Software for Ontario. *USDA Forest Service Proceedings RMRS-P-54*. 2008. doi: <https://www.researchgate.net/deref/http%3A%2F%2Fd.x.doi.org%2F10.13140%2F2.1.1633.6648>.
- Wulder MA, White JC, Cranny MM, Hall RJ, Luther JE, Beaudoin A, Goodenough DG, Dechka JA. 2008. Monitoring Canada's forests. Part 1: Completion of the EOSD land cover project. *Canadian Journal of Remote Sensing* 34(6): 549–562.
- Xiao CW, Ceulemans R. 2004. Allometric relationships for below- and aboveground biomass of young Scots pines. *Forest Ecology and Management* 203(1–3): 177–186.

Annex 3.6, Methodology for Waste Sector

- AECOM Canada. 2011. Improved methodology for the estimation of greenhouse gases from Canadian municipal wastewater treatment facilities.
- AECOM Canada. 2012. Evaluation of Canada's estimation methodology of nitrous oxide emissions from human sewage. Final report.
- Bond R, Straub CP, editors. 1973. *Handbook of environmental control*. Vol. 2, Solid Waste. Table 1.1-28: Composition and Analysis of Average Municipal Refuse. Cleveland (OH): CRC Press.
- Canada. 2012. *Fisheries Act: Wastewater Systems Effluent Regulations*. P.C. 2012-942, 2012 June 28, SOR/2012-139. Available online at: <https://laws-lois.justice.gc.ca/PDF/SOR-2012-139.pdf>.
- [CCME] Canadian Council of Ministers of the Environment. 2006. *Review of dioxins and furans from incineration in support of a Canada-wide standard review*. Report prepared for the Dioxins and Furans Incineration Review Group by A.J. Chandler & Associates Ltd.
- [CCME] Canadian Council of Ministers of the Environment. 2007. *Canada-wide standards for mercury. A report on compliance and evaluation – mercury from dental amalgam waste. A report on progress – mercury emissions and mercury-containing lamps*. Available online at: https://ccme.ca/en/res/cws_mercury_amalgam_e.pdf.
- [CCME] Canadian Council of Ministers of the Environment. 2010. *Canada-wide standard for mercury emissions (incineration & base metal smelting)*. 2010 Progress Report.
- Climate Action Reserve. 2009. Table B.6 Organic waste digestion project protocol. p. 66. [accessed 2010 Oct 12]. Available online at: http://www.climateactionreserve.org/how/protocols/organic-waste-digestion/dev/#version_1.0.
- [CRU] University of East Anglia Climatic Research Unit, Harris IC, Jones PD. 2019. Climatic Research Unit (CRU) Time-Series (TS) monthly high-resolution gridded multivariate climate dataset. Version 4.03. [accessed 2019 Jul]. Available via Centre for Environmental Data Analysis (CEDS) Web Processing Service (data.ceda.ac.uk).
- Environment Canada. 1996. *Perspectives on solid waste management in Canada: an assessment of the physical, economic and energy dimensions of solid waste management in Canada*. Vol. I. Prepared by Resource Integration Systems Ltd. for Hazardous Waste Branch, Environment Canada.

- Environment Canada. 1999. *Municipal solid waste incineration in Canada: an update on operations 1997–1998*. Prepared by Compass Environmental Inc. for Environment Canada and Federal Panel on Energy Research Development.
- Environment Canada. 2003. *Municipal solid waste incineration in Canada: An update on operations 1999–2001*. Prepared by A.J. Chandler & Associates in conjunction with Compass Environmental Inc. for Environment Canada.
- [ECCC] Environment and Climate Change Canada. 2020a. *National waste characterization report: the composition of Canadian municipal solid waste*. Ottawa (ON): Waste Reduction and Management Division, ECCC. Available online at: <https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/municipal-solid/statistics-trends.html> and <http://publications.gc.ca/site/eng/9.884760/publication.html>.
- [ECCC] Environment and Climate Change Canada. 2020b. *Waste incineration in Canada 2006–2019 – A summary of findings from surveys conducted in 2006–2018*. Unpublished internal Environment Canada Report. Ottawa (ON): Pollutant Inventories and Reporting Division, ECCC.
- [ECCC] Environment and Climate Change Canada 2020c. *Wood waste summary report final*. Unpublished internal Environment Canada Report. Ottawa (ON): Pollutant Inventories and Reporting Division, ECCC.
- [ECCC] Environment and Climate Change Canada. 2020d. *Literature review on emission factors for the composting process by feedstock type*. Unpublished internal report. Ottawa (ON): Pollutant Inventories and Reporting Division, ECCC.
- [ECCC] Environment and Climate Change Canada. 2020e. *Literature review on percent loss (%) from onsite leakages at off-farm anaerobic digestion systems*. Unpublished internal report. Ottawa (ON): Pollutant Inventories and Reporting Division, ECCC.
- [Envirosim] Envirosim Associates Limited. 2019. *Report on sludge production and characteristics for municipal WWTP in Canada*. Prepared for Environment and Climate Change Canada.[FAOSTAT] Food and Agriculture Organization, Statistics. Food Balances (2014–). [accessed 2020 Dec]. Available online at: <http://www.fao.org/faostat/en/#data/FBSGHD>. 2017. *Study of municipal solid waste landfill gas capture and use in Canada, 2017*. Unpublished report prepared for Environment and Climate Change Canada.
- [IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC guidelines for national greenhouse gas inventories*. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at: <http://www.ipccnggip.iges.or.jp/public/2006gl/index.html>.
- [IPCC] Intergovernmental Panel on Climate Change. 2019. *2019 IPCC refinement to the 2006 guidelines for national greenhouse gas inventories*. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at: <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>.
- Levelton BH. 1991. *Inventory of methane emissions from landfills in Canada*. Unpublished report prepared for Environment Canada by Levelton & Associates.
- Mahvi AH. 2008. Sequencing batch reactor: A promising technology in wastewater treatment. *Journal of Environmental Health Science & Engineering* 5: 79–90.
- Minister of Supply and Services Canada. 1987. *National inventory of municipal waterworks and wastewater systems in Canada 1986*. Cat. No. E94-81 / 1987.
- MWA Consultants Paprigan. 1998. *Increased use of wood residue for energy: potential barriers to implementation*. Final draft. Prepared for the Canadian Petroleum Producers Association (confidential internal document).
- [NCASI] National Council for Air and Stream Improvement. 2003. *Calculation tools for estimating greenhouse gas emissions from wood products manufacturing facilities*. National Council for Air and Stream Improvement, Inc.
- [NCASI] National Council for Air and Stream Improvement. 2020. *Memo: wood residuals landfilled from Canadian pulp and paper mills*. National Council for Air and Stream Improvement, Inc.
- Newfoundland Water Resources Portal. No date. Online Database and Webmap. [accessed 2018 Mar]. Available online at: <https://maps.gov.nl.ca/water/>.
- [NRCan] Natural Resources Canada. 1997. National Wood Residue Data Base. Natural Resources Canada (printouts from J. Roberts).
- [NRCan] Natural Resources Canada. 1999. *Canada's wood residues: a profile of current surplus and regional concentrations*. Prepared by the Canadian Forest Service, Industry, Economics and Programs Branch, Natural Resources Canada for the National Climate Change Process Forest Sector Table.
- [NRCan] Natural Resources Canada. 2005. *Estimated production, consumption and surplus mill wood residues in Canada—2004*. Prepared by the Forest Products Association of Canada for Natural Resources Canada.
- [NRCan] Natural Resources Canada. 2006. *Provincial/territorial disposal waste compositions (2002), an analysis of resource recovery Opportunities on Canada and the projection of greenhouse gas emission implications*. Natural Resources Canada.
- Ontario Ministry of the Environment. 1985. *Municipal wastewater treatment works in Ontario*. Report. Available online at: <https://archive.org/details/municipalwastewat26018>.
- [Québec] Government of Quebec. 2003. *Évaluation de performance de 522 ouvrages municipaux d'assainissement des eaux pour l'année 2002 : Ouvrages de surverse et stations d'épuration*. ISBN 2-550-41514-0. Available online at: <https://www.mamrot.gouv.qc.ca/>.
- [Québec] Government of Quebec. 2005. *Liste des stations d'épuration. Service du suivi des infrastructures*. Available online at: <https://www.mamrot.gouv.qc.ca/>.
- [Québec] Government of Quebec. 2013. *Liste des stations d'épuration. Service du suivi des infrastructures*. Available online at: <https://www.mamrot.gouv.qc.ca/>.

- SMi. 2016. Étude Nationale de la Composition des Déchets Solides 2014-2015. Report prepared for Environment Canada by Consultants S.M. Inc.
- Statistics Canada. 2009. Food Statistics. Catalogue No. 21-020-XIE.
- Statistics Canada. No date (a). Table: 38-10-0032-01 (formerly CANSIM 153-0041) *Disposal of waste, by source, Canada, provinces and territories (table)*. CANSIM (database). [accessed 2020 Sep 14]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3810003201>.
- Statistics Canada. No date (b). Table 17-10-0005-01 (formerly CANSIM 051-0001). Population estimates on July 1st, by age and sex. [accessed 2020 May 12]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000501>.
- Statistics Canada. No date (c). Table 17-10-0027-01 (Formerly CANSIM 051-0024). Archived - Estimates of population, Canada, provinces and territories (x 1,000), 1921 to 1971. [accessed 2019 Apr 1]. Available online at: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710002701>.
- Stericycle, ULC. 2014. *Environmental assessment registration – Stericycle waste transfer facility*. Submitted to Minister of Environment and Conservation – Director of Environmental Assessment, Government of Newfoundland and Labrador.
- Surampalli RY, Baumann ER. 1995. Sludge production in rotating biological contactors with supplemental aeration and an enlarged first stage. *Bioresource Technology* 54(3): 297-304.
- Taşeli BK. 2018. Point source pollution and climate change impact from sequential batch reactor wastewater treatment plant. *Global NEST Journal* 20(1): 33-41.
- Tchobanoglou G, Theisen H, Vigil S. 1993. *Integrated solid waste management: engineering principles and management issues*. New York (NY): McGraw Hill.
- [U.S. EPA] United States Environmental Protection Agency. 1995. *Compilation of air pollutant emission factors. Vol. I—Stationary point and area sources*. AP 42, 5th Edition. Chapter 2, Solid Waste Disposal. U.S. Environmental Protection Agency. Available online at: <https://www.epa.gov/technical-air-pollution-resources>.
- Washington State. 2014. *Rule Development Committee report: septic tank effluent values*. Draft report. Washington State Department of Health, Wastewater Management Program.

Annex 4, Comparison of Sectoral and Reference Approaches and the National Energy Balance

[ECCC] Environment and Climate Change Canada. 2016. *Updated Coal Emission, Energy Conversion and Oxidation Factors*. Unpublished study commissioned by Environment and Climate Change Canada.

[ECCC] Environment and Climate Change Canada. 2019. *Updated Carbon Dioxide Emission Factors for Coal Combustion*. Unpublished report. Gatineau (QC): Prepared by Kay J., Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.

[IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the National Greenhouse Gas Inventories Programme. Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K, editors. Kanagawa (JP): Institute for Global Environmental Studies. Available online at www.ipcc-nccc.iges.or.jp/public/2006gl/index.html.

Jaques AP. 1992. *Canada's Greenhouse Gas Emissions: Estimates for 1990*, Environmental Protection. Report No. EPS 5/AP/4. Conservation and Protection. Environment Canada.

McCann TJ. 2000. *1998 Fossil Fuel and Derivative Factors*. Report prepared by T.J. McCann and Associates for Environment Canada.

[NCASI] National Council for Air and Stream Improvement. 2011. *NCASI Spreadsheets for Calculating GHG Emissions from Pulp and Paper Manufacturing*. Version 3.3. National Council for Air and Stream Improvements. [revised 2013 Nov; cited 2020 Jan 10].

Statistics Canada. No date. *Report on Energy Supply and Demand in Canada*. Catalogue No. 57-003-X. Available online at: <https://www150.statcan.gc.ca/n1/en/catalogue/57-003-X>.

[U.S. EPA] United States Environmental Protection Agency. 2003. *Compilation of Air Pollutant Emission Factors—Vol. 1: Stationary Point and Area Sources, AP 42, 5th Edition, Section 1.6*. Washington (DC): U.S. Environmental Protection Agency.

Annex 5, Assessment of Completeness

[IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC National Greenhouse Gas Inventories Programme. Available online at: <https://www.ipcc-nccc.iges.or.jp/public/2006gl/>.

Annex 6, Emission Factors

AECOM Canada. 2011. *Improved methodology for the estimation of greenhouse gases from Canadian municipal wastewater treatment facilities*.

AMEC Earth & Environmental. 2006. *Identifying and updating industrial process activity data in the Minerals sector for the canadian greenhouse gas inventory*. AMEC Earth & Environmental.

Aoyama M, Angers DA, N'dayegamiye A, Bissonnette N. 1999. Protected organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications. *Canadian Journal of Soil Science* 79: 419–425.

Bhandral R, Bittman S, Kowalenko G, Buckley K, Chantigny MH, Hunt DE, Bounaix F, Friesen A. 2009. Enhancing soil infiltration reduces gaseous emissions and improves N uptake from applied dairy slurry. *Journal of Environmental Quality* 38: 1372–1382.

- Barton P, Simpson J. 1994. *The effects of aged catalysts and cold ambient temperatures on nitrous oxide emissions*. Mobile Sources Emissions Division, Environment Canada. MSED Report No. 94-21.
- BioMer. 2005. *Biodiesel demonstration and assessment for tour boats in the old port of Montreal and Lachine Canal National Historic Site*. Québec, BioMer. Final report.
- Boadi DA, Ominski KH, Fulawka DL, Wittenberg KM. 2004. *Improving estimates of methane emissions associated with enteric fermentation of cattle in Canada by adopting an IPCC (Intergovernmental Panel on Climate Change) Tier-2 methodology*. Final report submitted to the Greenhouse Gas Division, Environment Canada, by the Department of Animal Science, University of Manitoba, Winnipeg (MB).
- Briggs D. 1994. Forest Products Measurements and Conversion Factors: with Special Emphasis on the U.S. Pacific Northwest. College of Forest Resources, University of Washington, Seattle. Available online at: http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_book.asp.
- [CAC] Cement Association of Canada. 2015. Unpublished data on Canadian clinker production.
- [CAPP] Canadian Association of Petroleum Producers. 1999. *CH₄ and VOC emissions from the Canadian upstream oil and gas industry*. Vols. 1 and 2. Prepared for the Canadian Association of Petroleum Producers. Calgary (AB): Clearstone Engineering. Publication No. 1999-0010.
- Chai L, Kröbel R, MacDonald D, Bittman S, Beauchemin KA, Janzen HH, McGinn SM, Vanderzaag A. 2016. An ecoregion-specific ammonia emissions inventory of Ontario dairy farming: Mitigation potential of diet and manure management practices. *Atmospheric Environment* 126: 1–14.
- Chantigny MH, Angers DA, Beauchamp CJ. 2000. Decomposition of de-inking paper sludge in agricultural soils as characterized by carbohydrate analysis. *Soil Biology and Biochemistry* 32: 1561–1570.
- Chantigny MH, Angers DA, Rochette P, Bélanger G, Massé D, Côté D. 2007. Gaseous nitrogen emissions and forage nitrogen uptake on soils fertilized with raw and treated swine manure. *Journal of Environmental Quality* 36: 1864–1872.
- Chantigny MH, Rochette P, Angers DA, Bittman S, Buckley K, Massé D, Bélanger G, Eriksen-Hamel N, Gasser M. 2010. Soil nitrous oxide emissions following band-incorporation of fertilizer nitrogen and swine manure. *Journal of Environmental Quality* 39: 1545–1553.
- Chantigny MH, Royer I, Rochette P, Angers DA, Massé D, Benchaar C. 2012. Manure storage strategies altered nutrient availability and greenhouse gas emissions following application to soils. 3rd AQSSS-CSSS Joint Meeting/Congrès conjoint AQSSS-SCSS: Soils in a changing climate: Friend or foe?, Manoir St-Castin, Québec City, QC, Canada, June 3-8, 2012.
- Cheminfo Services Inc., and Clearstone Engineering Ltd. 2014. *Compilation of a national inventory of greenhouse gas and fugitive VOC emissions by the Canadian coal mining industry*. Final report submitted to the Energy Group, Pollutant Inventories and Reporting Division, Environment Canada.
- Cheminfo Services. 2005. *Improvements to Canada's greenhouse gas emissions inventory related to non-energy use of hydrocarbon products*. Markham (ON): Cheminfo Services Inc.
- Cheminfo Services. 2010. *Study of potential additions and updates to the industrial process sources of GHGs in the Canadian GHG inventory, and development of Canadian-specific methodologies and emission estimates for such sources*. Final Report. Markham (ON): Cheminfo Services Inc.
- Cheminfo Services. 2015. *Petrochemical production study: Carbon flows and GHG emissions*. Confidential Final Report. Markham (ON): Cheminfo Services Inc.
- [CEEDC] Canadian Energy End-Use Data Centre. 2003. *A review of energy consumption in Canadian oil sands operations, heavy oil upgrading 1990, 1994 to 2001*. Burnaby (BC): Simon Fraser University.
- Cleary J. 2003. *Greenhouse gas emissions from peat extraction in Canada: A life cycle perspective*. MSc thesis, McGill University, Montreal (QC). C₂GCR Report No. 2003-1. [CRA] Conestoga-Rovers and Associates. 2014. *Characterization of Coking Coal, Coke, and Coke By-Products for the Purpose of Developing Updated Carbon Dioxide Combustion Emission Factors*. Final report submitted to the Energy Group, Pollutant Inventories and Reporting Division, Environment Canada.
- [CSPA] Canadian Steel Producers Association. 2009. Industry-average carbon contents. Unpublished data.
- Environment Canada. 2006. *ERMD report 04-44: Greenhouse gas emissions from 1997-2005 model year light duty vehicles*. Unpublished Environment Canada internal report. Ottawa (ON): Emissions Research and Measurement Division, Environment Canada.
- Environment Canada. 2009. *ERMS Report 07-14A: N₂O Emissions from in-use Canadian Tier 1 vehicles, report A: Greenhouse gas emission rates*. Unpublished Environment Canada internal report. Ottawa (ON): Emissions Research and Measurement Section, Environment Canada.
- Environment Canada. 2015. *Review of country-specific HFCs emission estimations in the refrigeration and air conditioning sectors*. Edalatmanesh M, Niemi D. Unpublished report. Ottawa (ON).
- [ECCC] Environment and Climate Change Canada. 2017a. *Updated coal emission, energy conversion and oxidation factors*. Unpublished Environment Canada internal report. Ottawa (ON): Pollutant Inventories and Reporting Division.
- [ECCC] Environment and Climate Change Canada. 2017b. *Updated CO₂ Emission factors for gasoline and diesel fuel*. Unpublished report. Prepared by S. Tobin, Pollutant Inventories and Reporting Division, Environment and Climate Change Canada. Gatineau (QC).

- [ECCC] Environment and Climate Change Canada. 2018. *Waste incineration in Canada 1990-2008 – A summary of findings from surveys conducted in 2006-2018*. Unpublished Environment and Climate Change Canada internal report. Ottawa (ON): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- [ECCC] Environment and Climate Change Canada. 2021. GHGRP facility reported data. Unpublished data.
- [ECCC] Environment and Climate Change Canada. 2020b. Literature review on percent loss (%) from onsite leakages at off-farm anaerobic digestion systems. Unpublished internal Environment Canada Report. Ottawa (ON): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- [ECCC] Environment and Climate Change Canada. 2020c. Literature review on emission factors for the composting process by feedstock type. Unpublished internal report. Ottawa (ON): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- [ECCC] Environment and Climate Change Canada. 2021. New Marketable Natural Gas Emission Factors and Energy Content Values 1999 to 2019. Unpublished internal report. Ottawa (ON): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- [ECCC] Environment and Climate Change Canada. 2021c. Carbon Dioxide Emission Factors for Coal Combustion in Canada. DRAFT internal report. Ottawa (ON): Pollutant Inventories and Reporting Division, Environment and Climate Change Canada.
- [EERL] Energy and Emissions Research Laboratory. 2020. Improving upstream oil and gas emissions estimates with updated gas composition data. Prepared by D. Tyner and M. Johnson, EERL, Carleton University. Ottawa (ON).
- [FAO] Food and Agriculture Organization. 2010. *Forest product conversion factors for the UNECE region*. Geneva Timber and Forest Discussion Paper 49. Food and Agricultural Organization of the United Nations.
- Forge T, Kenney E, Hashimoto N, Neilsen D, ZebARTH B. 2016. Compost and poultry manure as preplant soil amendments for red raspberry: Comparative effects on root lesion nematodes, soil quality and risk of nitrate leaching. *Agriculture, Ecosystem and Environment* 223: 48–58.
- [FPL] Forest Products Laboratory. 2004. Fuel value calculator. 5th Ed. USDA Forest Service: Arlington, Virginia. Graham L, Rideout G, Rosenblatt D, Hendren J. 2008. Greenhouse Gas Emissions from Heavy-Duty Vehicles, *Atmospheric Environment* 42: 4665–4681.
- Garcia Bravo T. 2015. *Picea mariana (Mill.) B.S.P plantation on cutover peatland in Alberta (Canada): Evaluating the effect of fertilization and resulting carbon stocks*. MSc Thesis. University of Calgary. Calgary (AB), 103 pp.
- Glatzel S, Kalbitz K, Dalva M, Moore T. 2003. Dissolved organic matter properties and their relationship to carbon dioxide efflux from restored peat bogs. *Geoderma* 113: 397–411.
- Graham L, Rideout G, Rosenblatt D, Hendren J. 2008. Greenhouse gas emissions from heavy-duty vehicles. *Atmospheric Environment* 42: 4665–4681.
- Graham L, Belisle S L, Rieger P. 2009. Nitrous oxide emissions from light duty vehicle. *Atmospheric Environment* 43: 2031–2044.
- Grant RF, Juma NG, Robertson JA, Izaurrealde RC, McGill WB. 2001. Long-Term Changes in Soil Carbon under Different Fertilizer, Manure, and Rotation. *Soil Science Society American Journal* 65: 205–214.
- Hao X, Chang C, Travis GR, Zhang F. 2003. Soil carbon and nitrogen response to 25 annual cattle manure applications. *Journal of Plant Nutrient and Soil Science* 166: 239–245.
- Hayne S, Jenkins C, Garneau M. 2014. *Off-site GHG emissions from Canadian peat products*. Unpublished report. Pollutant Inventories and Reporting Division, Environment Canada.
- Hayne S, Verbicki M. 2011. *Aboveground biomass density of Canadian peatlands*. Unpublished report. Pollutant Inventories and Reporting Division, Environment Canada.
- [IAI] International Aluminum Institute. 2006. *The aluminum Sector greenhouse gas protocol (Addendum to the WRI/WBCSD Greenhouse Gas Protocol)*. International Aluminum Institute.
- ICF Consulting. 2004. *Update of methane and nitrous oxide emission factors for on-highway vehicles*. Prepared by ICF Consulting for the U.S. Environmental Protection Agency. Report No. 420-P-04-16.
- [IPCC] Intergovernmental Panel on Climate Change. 2000. *Good practice guidance and uncertainty management in national greenhouse gas inventories*. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at <http://www.ipcc-nngip.iges.or.jp/public/gp/english/>.
- [IPCC] Intergovernmental Panel on Climate Change. 2003. *Good practice guidance for land use, land-use change and forestry*. IPCC National Greenhouse Gas Inventories Programme. Available online at: <https://www.ipcc-nngip.iges.or.jp/public/gpglulucf/gpglulucf.html>.
- [IPCC] Intergovernmental Panel on Climate Change. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change National Greenhouse Gas Inventories Programme. Available online at <http://www.ipcc-nngip.iges.or.jp/public/2006gl/>.
- [IPCC] Intergovernmental Panel on Climate Change. 2014. *2013 supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi T, Krug T, Tanabe K, Srivastava N, Baasansuren J, Fukuda M, Troxler TG, editors. IPCC, Switzerland. Available online at: <http://www.ipcc-nngip.iges.or.jp/public/wetlands/>.

[IPCC] Intergovernmental Panel on Climate Change. 2019. *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories* [accessed 2020 May 22]. Volume 4: Agriculture, Forestry and Other Land Use. Intergovernmental Panel on Climate Change. Available online at: <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/>.

[IPCC/OECD/IEA] Intergovernmental Panel on Climate Change / Organisation for Economic Co-operation and Development / International Energy Agency. 1997. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*. Available online at <http://www.ipcc-nngip.iges.or.jp/public/gl/lnvs1.html>.

Izaurrealde RC, McGill WB, Robertson JA, Juma NG, Thurston JJ. 2001. Carbon balance of the Breton classical plots over half a century. *Soil Science Society American Journal* 65: 431–441.

Jaques AP. 1992. Canada's greenhouse gas emissions: Estimates for 1990. Ottawa (ON): *Environmental Protection Publications, Conservation and Protection, Environment Canada*. Report No. EPS 5/AP/4.

King B. 1994. *Management of methane emissions from coal mines: environmental, engineering, economic and institutional implications of options*. Report prepared by Neill and Gunter for Environment Canada.

Lactanet. 2021. Statistics from milk recording data. Vision 2000 [database].

Larney FJ, Janzen HH. 1996. Restoration of productivity to a desurfaced soil with livestock manure, crop residue, and fertilizer amendments. *Agronomy Journal* 88: 921–927.

Lemke RL, Baron V, Iwaasa A, Farrell R, Schoenau J. 2012. *Quantifying nitrous oxide emissions resulting from animal manure on pasture, range and paddock by grazing cattle in Canada*. Final report submitted to the Greenhouse Gas Division, Environment Canada, by Agriculture and Agri-Food Canada, Saskatoon (SK).

Liang BC, Hao XY, Schoenau J, Ma BL, Zhang TQ, MacDonald JD, Chantigny M, Dyck M, Smith WN, Malhi SS, Thiagarajan A, Lafond J, Angers D. 2021. Manure-induced carbon retention measured from long-term field studies in Canada. *Agriculture, Ecosystems and Environment* 321, 107619

Lynch DH, Voroney RP, Warman PR. 2005. Soil physical properties and organic matter fractions under forages receiving composts, manure or fertilizer. *Compost Science and Utilization* 13: 252–261.

Maillard É, Angers DA, Chantigny M, Lafond J, Pageau D, Rochette P, Lévesque G, Leclerc ML, Parent LÉ. 2016. Greater accumulation of soil organic carbon after liquid dairy manure application under cereal-forage rotation than cereal monoculture. *Agriculture, Ecosystems and Environment* 233: 171–178.

Maillard E, Angers DA, Chantigny M, Bittman S, Rochette P, Lévesque G, Hunt D, Parent LE. 2015. Carbon accumulates in organo-mineral complexes after long-term liquid dairy manure application. *Agriculture, Ecosystems and Environment* 202: 108–119.

Marinier M, Clark K, Wagner-Riddle C. 2004. *Improving estimates of methane emissions associated with animal waste management systems in Canada by adopting an IPCC Tier-2 methodology*. Final report submitted to the Greenhouse Gas Division, Environment Canada, by the Department of Land Resource Science, University of Guelph, Guelph (ON).

Marinier M, Clark K, Wagner-Riddle C. 2005. *Determining manure management practices for major domestic animals in Canada*. Final report submitted to the Greenhouse Gas Division, Environment Canada, by the Department of Land Resource Science, University of Guelph, Guelph (ON).

McCann TJ. 2000. *1998 fossil fuel and derivative factors*. Prepared by T.J. McCann and Associates for Environment Canada.

McNeil P., Waddington JM. 2003. Moisture controls on sphagnum growth and CO₂ exchange on a cutover bog. *Journal of Applied Ecology* 40(2): 354–367.

[NCASI] National Council for Air and Stream Improvement. 2011. *NCASI spreadsheets for calculating GHG emissions from Pulp and Paper Manufacturing*. Version 3.3. National Council for Air and Stream Improvements. [revised 2013 Nov; cited 2020 Jan 10].

[NCASI] National Council for Air and Stream Improvement. 2012. *Methane and nitrous oxide emissions from biomass-fired boilers and recovery furnaces*. Technical Bulletin No. 998. Research Triangle Park, N.C.: National Council for Air and Steam Improvement Inc.

Oak Leaf Environmental. 2017. *Memorandum, recommended non-road CH₄ and N₂O emission rates (Revision 2)*. Prepared for Environment and Climate Change Canada.

Paré T, Dinel H, Moulin AP, Townley-Smith L. 1999. Organic matter quality and structural stability of a Black Chernozemic soil under different manure and tillage practices. *Geoderma* 91: 311–326.

Pelster DE, Chantigny MH, Rochette P, Angers DA, Rieux C, Vanasse A. 2012. Nitrous oxide emissions respond differently to mineral and organic nitrogen sources in contrasting soil types. *Journal of Environmental Quality* 41: 427–435.

Petrinex. 2020. Alberta Public Data - Conventional Volumetric Data. [cited 2020 Oct 23]. Available online at: <https://www.petrinex.ca/PD/Pages/APD.aspx>.

Petrone RM, Waddington JM, Price JS. 2001. Ecosystem scale evapotranspiration and net CO₂ exchange from a restored peatland. *Hydrological Processes* 15: 2839–2845.

Petrone RM, Waddington JM, Price JS. 2003. Ecosystem-scale flux of CO₂ from a restored vacuum harvested peatland. *Wetlands Ecology and Management* 11: 419–432.

Radovan R, Hassani N. et al . 2012. *A statistical approach to carbon dioxide emission factors for coal consumed in Canada*. Unpublished Report. Gatineau (QC): Environment Canada, Pollutant Inventories and Reporting Division.

- Rees HW, Chow TL, ZebARTH B, Xing Z, Toner P, Lavoie J, Daigle JL. 2014. Impact of supplemental poultry manure application on potato yield and soil properties on a loam soil in north-western New Brunswick. *Canadian Journal of Soil Science* 94: 49–65.
- Rochette P, Angers DA, Chantigny MH, Gagnon B, Bertrand N. 2008. N₂O fluxes in soils of contrasting textures fertilized with liquid and solid dairy cattle manures. *Canadian Journal of Soil Science* 88: 175–187.
- Rochette P, Chantigny MH, Ziadi N, Angers DA, Bélanger G, Charbonneau E, Pellerin D, Liang BC, Bertrand N. 2014. Soil nitrous oxide emissions after deposition of dairy cow excreta in eastern Canada. *Journal of Environmental Quality* 43: 829–841.
- SGA Energy. 2000. *Emission factors and uncertainties for CH₄ & N₂O from fuel combustion*. Unpublished report prepared by SGA Energy Limited for the Greenhouse Gas Division, Environment Canada.
- Sheppard SC, Bittman S, Swift ML, Beaulieu M, Sheppard MI. 2011a. Ecoregion and farm size differences in dairy feed and manure nitrogen management: A survey. *Canadian Journal of Animal Science* 91: 459–473.
- Sheppard SC, Bittman S, Swift ML, Tait J. 2010. Farm practices survey and modelling to estimate monthly NH₃ emissions from swine production in 12 Ecoregions of Canada. *Canadian Journal of Animal Science* 90: 145–158.
- Sheppard SC, Bittman S, Swift ML, Tait J. 2011b. Modelling monthly NH₃ emissions from dairy in 12 Ecoregions of Canada. *Canadian Journal of Animal Science* 91(4): 649–661.
- Skog KE. 2008. Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal* 58: 56–72.
- Sommerfeldt TG, Chang C, Entz T. 1988. Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. *Soil Science Society American Journal* 52: 1668–1672.
- Statistics Canada. 2014. *Report on Energy Supply and Demand in Canada (annual)*. Catalogue No. 57-003-X. Ottawa, Ontario.
- Steenberg J, Ristow M, Duinker P, MacDonald D, Samson C, Flemming C. 2021. *An updated approach for assessing Canada's urban forest carbon storage and sequestration*. Internal report. Ottawa (ON): Environment Canada.
- Strack M, Zuback Y. 2013. Annual carbon balance of a peatland 10 yr following restoration. *Biogeosciences* 10: 2885–2896.
- Strack M, Keith A, Xu B. 2014. Growing season carbon dioxide and methane exchange at a restored peatland on the Western Boreal Plain. *Ecological Engineering* 64: 231–239.
- Taşeli BK. 2018. Point source pollution and climate change impact from sequential batch reactor wastewater treatment plant. *Global NEST Journal* vol. 20.
- [U.S. EPA] United States Environmental Protection Agency. 1995. *Compilation of air pollutant emission factors*. 5th Edition. Vol. 1, Chapter 2.2, Sewage Sludge Incineration. U.S. Environmental Protection Agency. Available online at <https://www.epa.gov/technical-air-pollution-resources>.
- [U.S. EPA] U.S. Environmental Protection Agency. 1998. Emission factor documentation for Ap-42 section 2.4 Municipal solid waste landfills revised.
- [U.S. EPA] United States Environmental Protection Agency. 1996. *Compilation of air pollutant emission factors—Vol. 1: Stationary point and area sources, AP 42, 5th Edition, Supplement B, Section 1.9 and 1.10*. Washington (DC): U.S. Environmental Protection Agency.
- [U.S. EPA] United States Environmental Protection Agency. 2003. *Compilation of air pollutant emission factors—Vol. 1: Stationary point and area sources, AP 42, 5th Edition, Section 1.6*. Washington (DC): U.S. Environmental Protection Agency.
- [U.S. EPA] United States Environmental Protection Agency. 2010. *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008*. Washington (DC): U.S. Environmental Protection Agency.
- Waddington JM, Day SM. 2007. Methane emissions from a peatland following restoration. *Journal of Geophysical Research* 112: 1–11.
- Waddington JM, Price JS. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography* 21(5): 433–451.
- Waddington JM, Strack M, Greenwood MJ. 2010. Toward restoring the net carbon sink function of degraded peatlands: Short-term response in CO₂ exchange to ecosystem-scale restoration. *Journal of Geophysical Research* 115: 1–13.
- Waddington JM, Toth K, Bourbonniere R. 2008. Dissolved organic carbon export from a cutover and restored peatland. *Hydrological Processes* 22: 2215–2224.
- Waddington JM, Warner KD. 2001. Atmospheric CO₂ sequestration in restored mined peatlands. *Ecoscience* 8(3): 359–368.
- Waddington JM, Warner KD, Kennedy GW. 2002. Cutover peatlands: A persistent source of atmospheric CO₂. *Global Biogeochemical Cycles* 16: 1–7.
- White T, Luckai N, Larocque GR, Kurz WA, Smyth C. 2008. A practical approach for assessing the sensitivity of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). *Ecological Modelling* 219(3–4): 373–382.
- [WBCSD] World Business Council for Sustainable Development. 2005. *CO₂ accounting and reporting standard for the cement industry, version 2.0*. Switzerland.

Annex 7, Ozone and Aerosol Precursors

- [UNFCCC] United Nations Framework Convention on Climate Change. 2014. *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013*, Decision 24/CP.19. FCCC/CP/2013/10/Add.3. Available online at: <https://unfccc.int/sites/default/files/resource/docs/2013/cop19/eng/10a01.pdf>.