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SUMMARY

Canada produced 729 megatonnes of greenhouse gas (GHG) emissions in 2018 and approximately 10 per cent of that came from the country's agricultural sector. Different farming operations produce varying amounts of GHGs, whether they are small animal or crop farms, or large beef cattle operations. Besides field techniques, researchers are using models such as HOLOS – a Canadian whole-farm emissions model – and the Integrated Farm Systems Model, among others, to find ways to target emission sources without hampering a farm's financial sustainability and production. Other models focus on simulating the productivity and impact of cropping systems on the environment, with the goal of estimating the level of emissions. Other models are used to derive management-driven soil carbon change factors.

Carbon footprints vary for every subsector of agriculture and assessing them is a complex effort that involves accounting for every process that occurs throughout production. Methane and nitrous oxide are the main GHGs that agriculture emits at 38 and 36 per cent respectively, with carbon dioxide responsible for the remaining 26 per cent. GHGs arise from enteric fermentation of cattle, the application of synthetic and organic fertilizer, biomass decomposition, soil cultivation and tillage, mineralization of soil organic matter and manure, among other sources.

There are many options available for reducing agricultural GHG emissions, depending on the type of farm operation. Soil carbon content can be increased and stored in the soil or in plants to cut CO_2 losses to the atmosphere. Carbon storage can be achieved by using cover crops or mulches and switching from annual to perennial cropping, for example. No-till practices permit the soil to develop porosity with better moisture retention and organic matter buildup, creating a healthy environment for roots, microorganisms and fungi.

Manure emissions can be managed by capturing CH_4 (methane) and using it to generate heat and electricity. Manure piles can also be aerated to reduce emissions.

* Environmental Soil Scientist, Independent Consultant, Calgary, Alberta, Canada.

† Professor, Canada Research Chair, Tier I, Climate Change, Energy and Sustainability Policy, Centre for the Study of Science and Innovation Policy, Johnson-Shoyama Graduate School of Public Policy, University of Regina.

‡ Research Scientist, Agriculture and Agri-Food Canada.

Energy consumption from farm equipment can be reduced through sustainable practices such as reducing tillage, retaining residue and managing mixed-species forests, as well as reducing pesticide and fertilizer applications through diverse cropping systems. In addition to saving fuel consumption, sustainable practices minimize soil erosion. Other sustainable practices include avoiding clear-cutting, contour plowing and using mulches and compost to increase the soil's carbon and nutrient content.

Consumers can make a significant difference in reducing agricultural GHG emissions by making informed choices when purchasing food. Eating a balanced diet that includes a variety of sources of protein can contribute to reducing emissions. Multi-product farm systems that integrate cropping, dairy and beef production have a lower carbon footprint and higher production efficiencies compared to single-product farm systems.

INTRODUCTION

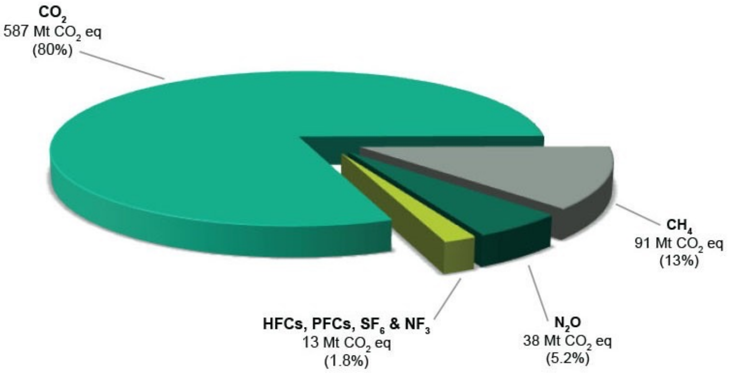
Greenhouse gases (GHG) absorb and emit infrared radiation and cause the warming of the planet's surface. Although this warming is vital for life on Earth, accelerated surface temperature rises due to increased GHGs in the atmosphere result in increasing atmospheric energy and rates of evaporation. This causes unpredictable weather patterns such as heat waves, more intense and frequent droughts, wildfires and more intense precipitation events. Desertification and land degradation are putting global food security and terrestrial ecosystems at risk (IPCC 2019).

The main GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). These gases have different radiative forces and global warming potentials. To standardize the units, carbon dioxide equivalent (CO_2-eq) is used by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential over a 100-year time horizon. For example, methane and nitrous oxide have global warming potentials of 25 and 298, respectively. Thus, emitting one tonne of methane and nitrous oxide is equivalent to emitting 25 and 298 tonnes of carbon dioxide, respectively (Krey et al. 2014; Hausfather 2009).

Carbon is an essential ingredient to life on Earth and is found in animals, plants, soils, rocks, oceans and in the atmosphere (Giovannelli et al., 2017, Riebeek 2011). Humans use carbon in food systems, buildings, clothing and energy needs. The carbon cycle describes its movement between different pools and its constant transfer from one form to another: from rocks and fossilized carbon pools to the atmosphere, from plant material to the atmosphere and back, and so on (Harrison 2003). During photosynthesis, plants take up carbon (in the form of carbon dioxide) from the atmosphere to produce sugars and energy for biomass and grain production. Humans affect the carbon cycle by changing the speed at which carbon transfers from one pool to another; this in turn affects the amount of carbon in its different forms. Through harvesting fossilized carbon pools from deep rock formations, carbon is brought to the Earth's surface and released into the atmosphere at a faster rate than through natural conditions. In addition, clearing forests reduces the ability of photosynthesis to remove carbon dioxide from the atmosphere and releases carbon stored in the living biomass. The atmosphere is a smaller carbon pool compared to oceans and terrestrial reservoirs, and its composition is being affected by increased carbon in the form of carbon dioxide (Harrison 2003; Falkowski 2000).

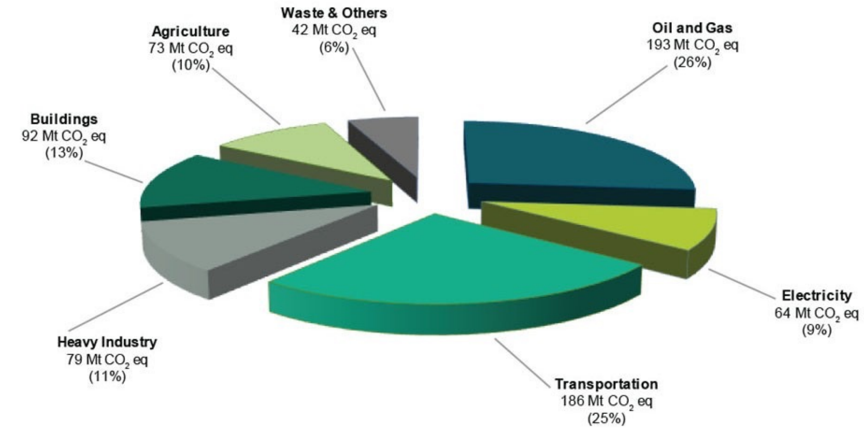
In Canada, total GHG emissions in 2018 reached 729 megatonnes of carbon dioxide equivalent (Mt CO_2 eq) (ECCC 2018) with about 80 per cent emitted in the form of CO_2 (Fig. 1). Methane (CH_4) emissions consist mainly of fugitive emissions generated by oil and natural gas systems, coal mining, agriculture and animal waste management systems, landfills and wastewater. Nitrous oxide (N_2O) emissions result from agricultural soil management, energy and fuel combustion, industrial processes and waste management.

Figure 1: The contribution of major GHGs to Canada's total emissions (ECCC 2018)



The breakdown by sector (Fig. 2) shows that the majority of GHG emissions in Canada (approximately 84 per cent) are produced by oil and gas, transportation, buildings, heavy industry and electricity. Of the remaining 16 per cent, approximately 10 per cent of emissions are produced by the agricultural sector (ECCC 2018).

Figure 2: GHG emissions by sector (ECCC 2018)



Agriculture is a major industry and a key driver of the Canadian economy. In 2016, agriculture and agri-food production generated $111.9 billion of the gross domestic product (GDP), accounting for 6.7 per cent of Canada's total GDP (Agriculture and Agri-Food Canada 2017). More recently, the agricultural industry generated $48 billion of GDP in March 2021 (Trading Economics 2021). Agricultural operations emit significant amounts of GHGs into the atmosphere and mitigation is part of many climate change response plans.

The next sections will present GHG emission estimates from Canadian agriculture with an overview followed by estimates from specific subsectors. Current techniques, models and methods of estimation will also be discussed. Therefore, the aim of this paper is two-fold: 1) present current Canadian agricultural emission estimates in major agricultural sub-sectors, and 2) discuss current techniques, models and methods of GHG emission estimation.

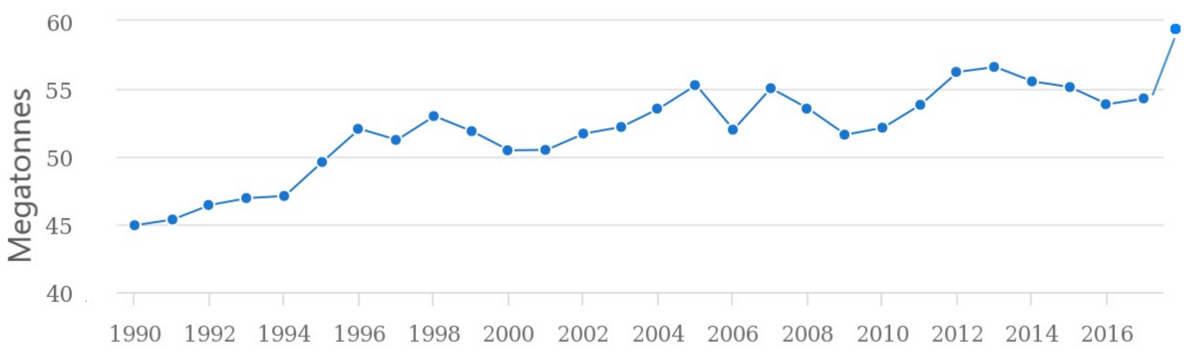
GHG EMISSION ESTIMATES FROM CANADIAN AGRICULTURE

Agriculture covers about five per cent of Canada's land mass (Statistics Canada 2017a), and about 80 per cent of the agricultural land is located in the Prairie Provinces: Manitoba, Saskatchewan and Alberta. Major agricultural land uses include cultivated lands (37.7 million ha) and grasslands (19.3 million ha) (Statistics Canada 2017a). Main crops include grains: wheat, rye, barley, corn and oats; oilseeds: canola, soybeans, flax and sunflower; pulses and specialty crops: lentils, peas, beans, potatoes and sugar beets; and forage crops: alfalfa. Livestock production in Canada includes 12.5 million cattle (Statistics Canada 2017b), 0.9 million dairy cows (Statistics Canada 2017b), 14 million pigs (Statistics Canada 2017c), 145.5 million hens and chickens (Statistics Canada 2017d) and one million sheep and lambs (Statistics Canada 2017e).

Every agricultural product emits GHGs as a result of its production. Agricultural subsectors vary in their carbon footprint and estimating their footprint requires accounting for every process that takes place during production.

Agricultural GHG emissions in Canada have increased since 1990 from 45 Mt CO_2 eq to 59 Mt in 2018 (Fig. 3) (FAOSTAT 2018) following an increase in agricultural gross domestic product reaching C$40 billion in 2018 (Trading Economics 2020). The increase in GHG emissions corresponds to 8.1 per cent of total GHG emissions in Canada (ECCC 2018). However, this does not include energy sources of emissions from production processes, transportation and fugitive emissions during the production of nitrogen fertilizers. Adding these energy emissions would increase the GHG emissions of Canadian agriculture to 87.4 Mt CO_2 eq or 12 per cent of total GHG emissions in Canada (Desjardins et al. 2020).

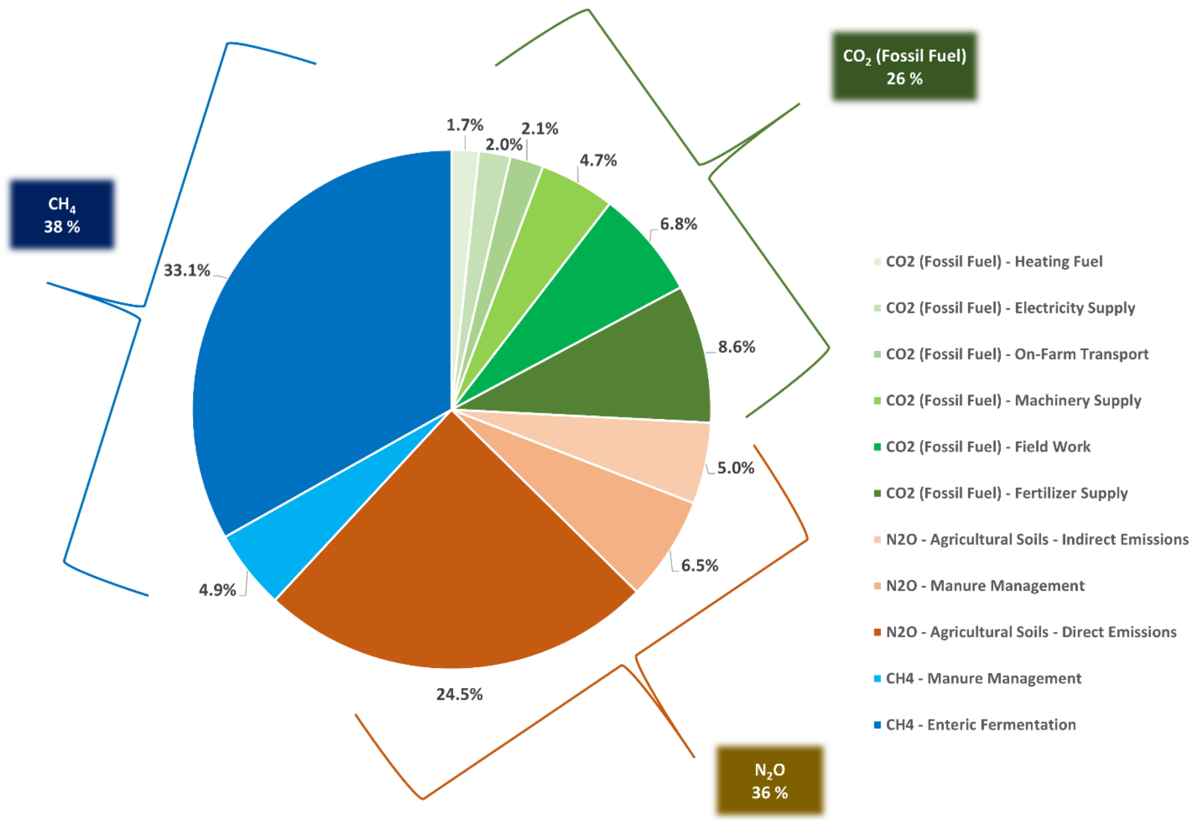
Figure 3: Agricultural GHG emissions in Canada (Mt CO_2 eq) between 1990 and 2017 (FAOSTAT 2018)



Note: Data do not include energy sources of emission from production processes, transportation and fugitive emissions during the production of nitrogen fertilizers.

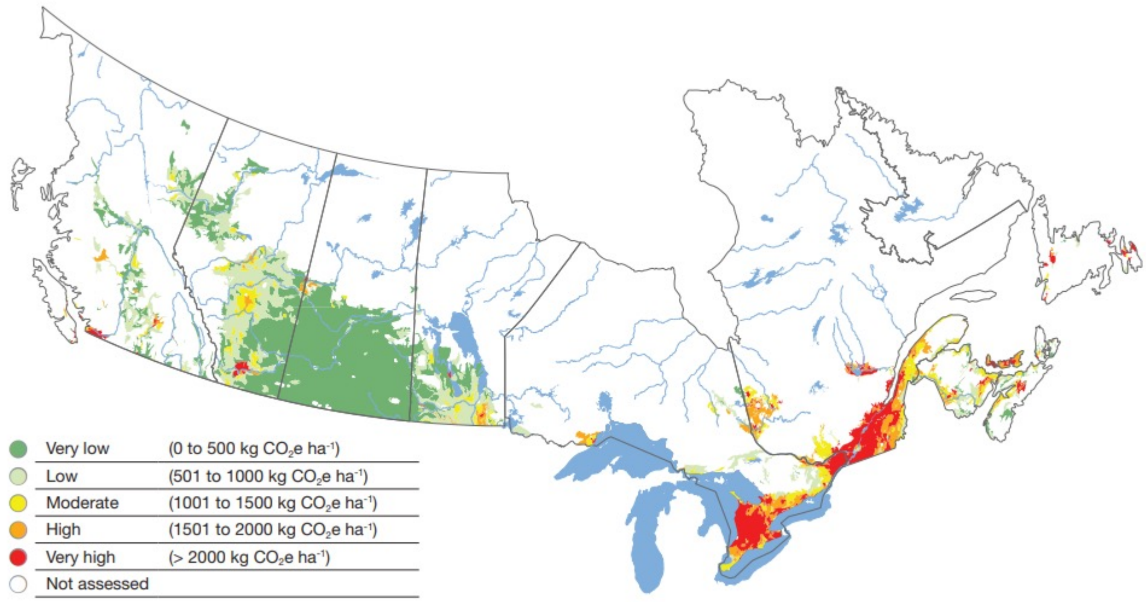
The main GHGs emitted by agricultural activities are nitrous oxide and methane. Carbon dioxide is emitted from soils and from the use of fossil fuels for machinery and farm transportation, electricity and heating needs. Carbon dioxide emissions account for approximately 26 per cent of agricultural emissions. Nitrous oxides account for approximately 36 per cent of agricultural emissions (in CO_2 eq) through direct release from soils and manure management. Methane emissions account for approximately 38 per cent of agricultural emissions (in CO_2 eq) and occur through enteric fermentation and manure management (Fig. 4).

Figure 4: Relative magnitude of the main GHG emissions in Canadian agriculture in 2015 (Desjardins et al. 2020)



Agricultural practices are both a source and a sink of GHGs. The removal of atmospheric CO_2 by soils, also known as soil carbon sequestration, resulted in a decline in net GHG emissions (emissions minus removal by soil) between 1981 when the soils were a source and 2011. This was evident in the Canadian prairies after the widespread adoption of beneficial management practices (BMPs) such as reduced tillage, decreased summer fallow, more cover crops and an increase in perennial instead of annual cropping systems (Ahmed et al. 2020; Fan et al. 2019; Worth et al. 2016). Net GHG emissions per hectare are generally higher in Eastern Canada than in Western Canada (Fig. 5) which is mainly a result of the adoption of BMPs in the West that enhance soil carbon sequestration. The wetter climate in Eastern Canada frequently causes higher emissions of N_2O, especially with crops that are more demanding in nitrogen fertilizers such as corn.

Figure 5: Net agricultural GHG emissions per hectare of land (kg CO_2 eq ha^{-1}) in Canada in 2011 (Worth et al. 2016)

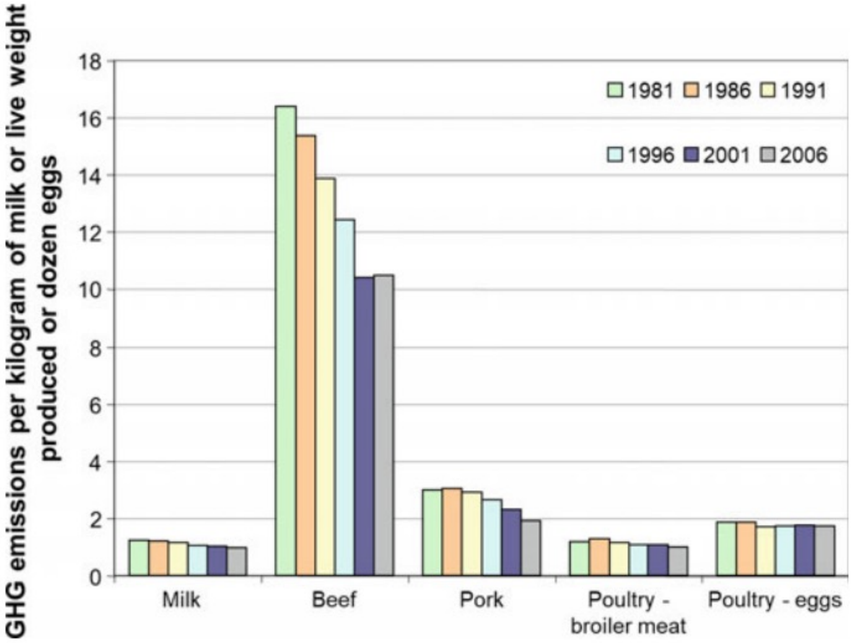


1. GHG EMISSIONS IN CANADIAN LIVESTOCK PRODUCTION

According to the National Inventory Report (NIR), current GHG emissions from Canadian livestock production are estimated at 32 Mt CO_2 eq or 53 per cent of total agricultural emissions (ECCC 2020).

GHG emission intensities from Canadian livestock production decreased between 1981 and 2006, especially for beef and pork production (Fig. 6). This decrease is mainly the result of improved management practices, better crop yields and livestock feed and more productive livestock breeds (Desjardins et al. 2020). These estimated emissions did not include changes in soil carbon.

Figure 6: GHG emissions per kg of milk or live weight or dozen eggs in Canada in 1981–2006 (Desjardins et al. 2020)

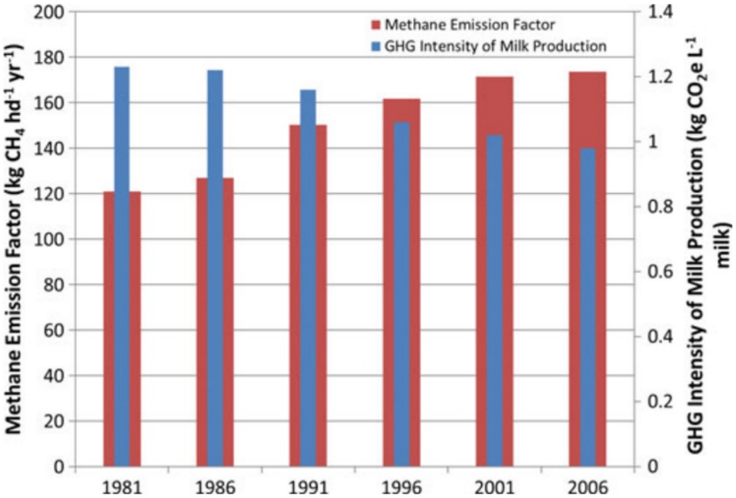


Legesse et al. (2016) used the Holos model, a Canadian whole-farm emissions model, to compare emissions from the production of Canadian beef cattle between 1981 and 2011. They found that total GHG emissions were 28 per cent higher in 2011 than in 1981 (28.3 teragrams (Tg) of CO_2 eq vs. 22.1 Tg CO_2 eq). On an intensity basis, however, CO_2 eq per kg of liveweight (excluding culled dairy cows) decreased in 2011 by 18 per cent to 12.0 kg CO_2 eq compared to 14.0 in 1981. This decline resulted from a drop in CH_4 (18 per cent), N_2O (19 per cent) and CO_2 (16 per cent) emissions.

For comparison, Rotz et al. (2019) used the Integrated Farm Systems Model, a whole-farm systems model, to estimate annual GHG emissions for beef cattle production in the U.S. They found an emission intensity of 21.3 ± 2.3 CO_2 eq per kg carcass weight from field to farm gate. In Brazil, Cardoso et al. (2016) used a life-cycle analysis approach and estimated an annual GHG emission intensity ranging from 29.4 to 58.3 kg CO_2 eq per kg carcass weight, depending on various production scenarios.

Desjardins et al. (2020) estimated CH_4 emissions per cow and GHG emissions per litre of milk production in Canada and found that CH_4 emissions per cow increased between 1981 and 2006 while the GHG emissions per litre of milk decreased (Fig. 7) due to the increased milk production per animal. This means that the number of cows needed to produce the same amount of milk has declined over time (Desjardins et al. 2020).

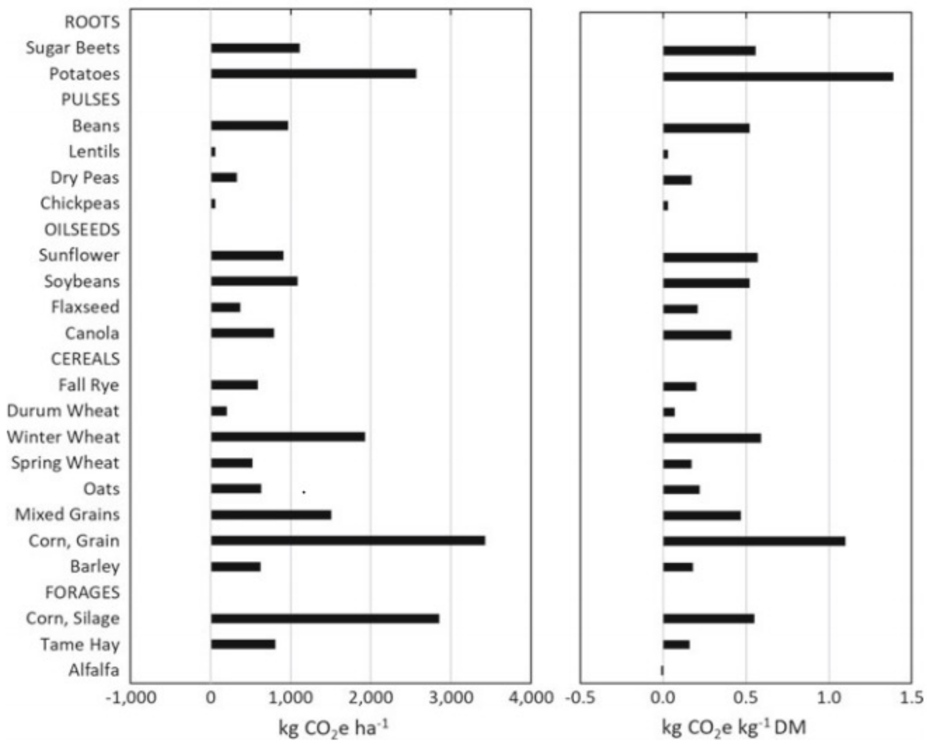
Figure 7: CH_4 emissions per cow and GHG emissions per litre of milk production in Canada in 1981–2006 (Desjardins et al. 2020)



2. GHG EMISSIONS IN CANADIAN CROP PRODUCTION

Whether in kg of CO_2 eq per hectare or in kg of CO_2 eq per kg of dry matter produced, GHG emissions from cropping systems can be estimated for the major crops produced in Canada (Fig. 8). These emissions were estimated using production and fertilizer data from Statistics Canada, and the changes in soil carbon were accounted for (Desjardins et al. 2020). Low values show that some crops require lower fertilizer inputs (alfalfa, lentils, chickpeas) than crops with higher GHG emission intensities (corn, potatoes). Crops with low GHG emission intensities are usually legumes such as alfalfa and soybeans which can fix nitrogen and have high soil carbon sequestration.

Figure 8: Average estimates of GHG emissions per hectare and per kg of dry matter for major Canadian crops in 2011 (Desjardins et al. 2020)



Conditions vary across Canada and crop emission estimates differ in each province as shown in Table 1. Weather condition and humidity levels affect soil water contents and plants' water and nutrient uptake as well as nutrient leaching, affecting fertilizer inputs and nitrous oxide emissions. In addition, the increased adoption of best management practices favouring carbon sequestration (no-till, reduced summer fallow) in the Prairie Provinces, combined with drier weather conditions resulting in lower nitrous oxide emissions, contribute to reducing the agricultural carbon footprint in that region. In addition, large farm fields on the prairies allow more efficient use of fossil fuels than smaller field sizes in Eastern Canada.

Table 1: Average GHG emission estimates in kg CO_2 eq per hectare for major Canadian crops by province (Desjardins et al. 2020)

Group averages	Oilseeds	Pulses	Roots	Forages	Cereals	Oilseeds	Canola	Flaxseed	Soybeans	Sunflower
Atlantic provinces	860		3300	1440	2030				860	
Québec	1970		3530	1780	2680		2700		1240	
Ontario	1980	1360	2890	1770	2330		2740		1220	
Manitoba	680	350	1500	650	1000		1000	650	140	910
Saskatchewan	400	90	700	−180	160		530	270		
Alberta	900	530	1340	580	770		1010	780		
British Columbia	1580		2380	1200	1180		1580			

Pulses and roots	Chickpeas	Dry peas	Beans	Lentils	Potatoes	Sugar beets	Forages	Alfalfa	Tame hay	Corn silage
Atlantic Provinces					3300			380	1320	2610
Québec					3530			580	1240	3530
Ontario			1360		2890			600	1310	3390
Manitoba		460	230		1500			−120	510	1550
Saskatchewan	20	180		60	700			−380	30	
Alberta	430	700	470		1560	1110		−130	390	1480
British Columbia					2380			140	850	2600

Cereals	Barley	Grain corn	Mixed grains	Oats	Spring wheat	Winter wheat	Durum wheat	Fall rye
Atlantic provinces	1650	2780	1650	1960	2020	2130		
Québec	2250	3630	2270	2590	2610	2700		
Ontario	1930	3480	1940	2240	2100	2450		2200
Manitoba	830	1550		900	890	950		880
Saskatchewan	180			200	170	160	140	130
Alberta	690	1430	750	690	690	640	630	600
British Columbia	1140			1180	1210			

Vegetable and fruit crops also emit GHGs in the form of CO_2 and N_2O. Dyer and Desjardins (2018) estimated these emissions by province, assuming these crops were irrigated field-grown crops with the exception of potatoes. GHG emissions are presented by area and by kg fresh weight in Table 2.

Table 2: Average GHG emission estimates for major field-grown Canadian vegetables and fruits per unit area and weight in 2007–2016 (Desjardins et al. 2020)

Vegetables	AP	QC	ON	BC	AP	QC	ON	BC
	kg CO_2e ha^{-1}				kg CO_2e kg^{-1} fresh weight			
Carrots	3100	3100	3400	3000	0.1	0.1	0.1	0.1
Sweet corn	2300	2600	2900	2600	0.4	0.3	0.2	0.4
Tomatoes	3700	4000	7000	4200	0.3	0.2	0.1	0.2
Peas	1300	1400	1500	1500	0.6	0.3	0.3	0.3
Lettuce	2500	3200	3100	3500	0.4	0.1	0.2	0.1
Cabbage	3800	4400	4000	3800	0.1	0.1	0.1	0.2
Potatoes	2900	2800	2600	2500	0.1	0.1	0.1	0.1
Fruits								
Blueberries	1700	1500	1400	1700	1.2	1.5	0.4	0.3
Peaches	2200	n/a	1900	2100	0.2	n/a	0.2	0.2
Apples	1800	1600	1400	1800	0.1	0.1	0.1	0.1
Strawberries	2300	2200	1900	2100	0.4	0.3	0.4	0.4
Grapes	1500	1400	2100	1800	0.4	0.5	0.2	0.3

n/a—Not applicable, no significant production in this region

AP: Atlantic Provinces, QC: Québec, ON: Ontario, and BC: British Columbia.

The above GHG emission intensities from livestock and crop production were gathered into Table 3 below. Production data and production areas were sourced from Statistics Canada, and GHG emission estimates were calculated by multiplying the intensities by total production for each commodity. Total calculated GHG emissions (71 Mt) did not differ significantly from the estimated total value of 59 Mt reported in the National Inventory Report (ECCC 2020).

Table 3: Summary of GHG emission intensity estimates, total production, estimated total emissions and contribution to overall production for livestock and crop production in Canada. (Sources: Desjardins et al. 2020; ECCC 2020; Statistics Canada 2016a-j)

Canadian Product / GHG Source Category	**GHG Emission Intensity**	**Year**	**2016 Production**	**Production Area**	**2016 Estimated GHG Emissions** (Calculated)	**Contribution to Overall Emissions**	**2018 Estimated GHG Emissions** (NIR)
	kg CO_2 eq / kg liveweight, or L, or dozen eggs		kg liveweight, L or dozen eggs	Ha in 2016	kg CO_2 eq	%	kt CO_2 eq
Enteric Fermentation (CH_4)							24,000
Manure Management							7,900
Agricultural Soils (N_2O)							25,000
Crop Residue Burning (CH_4 and N_2O)							50
Lime and Urea Application (CO_2)							2,600
Livestock and Livestock-Related Products							
Cattle	12	2011	1,868,300,000	-	22,419,600,000	**31.66**	-
Hogs	2	2006	3,522,259,000	-	7,044,518,000	9.95	-
Poultry	1.00	2006	436,558,698	-	436,558,698	0.62	-
Milk	0.96	2006	8,440,863,000	-	8,103,228,480	11.44	-
Eggs	1.90	2006	746,389,000	-	1,418,139,100	2.00	-
Crop Production							
	kg CO_2 eq / ha			ha	kg of CO_2 eq	%	
Spring Wheat	550		-	6,422,500	3,532,375,000	4.99	-
Winter Wheat	1,900		-	733,100	1,392,890,000	1.97	-
Durum Wheat	160		-	2,469,200	395,072,000	0.56	-
Fall Rye	600		-	186,000	111,600,000	0.16	-
Canola	750		-	8,410,900	6,308,175,000	8.91	-
Barley	600		-	2,701,800	1,621,080,000	2.29	-
Oats	650		-	1,232,300	800,995,000	1.13	-
Corn for Grain	3,450		-	1,452,200	5,010,090,000	7.07	
Mixed Grain	1,500		-	177,000	265,500,000	0.37	-
Sunflower Seed	960		-	28,300	27,168,000	0.04	-
Soybeans	1,100		-	2,269,200	2,496,120,000	3.52	-
Flaxseed	370		-	381,000	140,970,000	0.20	-
Lentils	60		-	2,253,600	135,216,000	0.19	-
Beans	980		-	122,000	119,560,000	0.17	-
Dry Peas	350		-	1,732,600	606,410,000	0.86	-
Chickpeas	60		-	57,800	3,468,000	0.00	-
Sugar Beets	1,150		-	11,500	13,225,000	0.02	-
Corn for Silage	2,800		-	364,200	1,019,760,000	1.44	-
Tame Hay	760		-	5,882,600	4,470,776,000	6.31	-
Alfalfa	-		-	-	-	-	-
Vegetable and Fruit Production							
	kg CO_2 eq / ha			ha	kg of CO_2 eq	%	
Carrots	12,600	2016	-	8,940	112,644,000	0.16	-
Sweet corn	10,400	2016	-	19,248	200,179,200	0.28	-
Tomatoes	18,900	2016	-	6,938	131,128,200	0.19	-
Peas	5,700	2016	-	12,782	72,857,400	0.10	-
Lettuce	12,300	2016	-	4,140	50,922,000	0.07	-
Cabbage	16,000	2016	-	5,578	89,248,000	0.13	-
Potatoes	10,800	2016	-	140,187	1,514,022,000	2.14	-
Blueberries	6,300	2016	-	79,329	499,772,700	0.71	-
Peaches	6,200	2016	-	2,664	16,516,800	0.02	-
Apples	6,600	2016	-	17,676	116,661,600	0.16	-
Strawberries	8,500	2016	-	4,110	34,935,000	0.05	-
Grapes	6,800	2016	-	12,627	85,863,600	0.12	-
				Sum of Emissions	70,817,244,778	kg	
					Calculated		**NIR**
				kt	70,817		59,550
				Mt	**70.82**		**59.55**

METHODOLOGIES FOR ESTIMATING GHG EMISSIONS

Methods used to estimate GHG emissions include all phases of production from seeding to farm gate. Emissions reported in the NIR are estimated using mass balance and chemical reaction calculations (stoichiometry) under average conditions. Emission factors are also used in combination with specific activity data to produce estimates at a larger scale, such as either by sector or by province (ECCC 2018). These regional estimates are usually the result of measuring spatially diffuse sources of emissions such as transportation and agricultural land management. However, calculating long-term GHG emissions from such sources often requires the use of simulation models.

Some agricultural practices can also remove GHGs from the atmosphere, such as crop growth and soil carbon sequestration. These are complex, long-term, natural and anthropogenic systems which vary over space and time and require a combination of repeated data collection and modelling for best emissions estimates.

1. FIELD MEASUREMENTS

Researchers have conducted long-term in-situ measurements of soil organic carbon change and GHG fluxes from agricultural soils while comparing land uses and managements. Desjardins et al. (2020) describe these methods in detail. They include soil cores, chamber techniques that quantify CO_2, CH_4 and N_2O soil uptake and release from soil, and meteorological techniques such as mass balance and inverse modelling. Other methods include tower-based flux systems which measure N_2O emissions and aircraft-based N_2O and CH_4 flux measurements. These can be combined with modelling to scale up to the regional level of emissions estimation. Desjardins et al. (2018) address the challenges of regional measurements of agricultural CH_4 emissions.

2. MODELS

Modelling GHG emissions and carbon change in Canada has been conducted with both process and empirical models (Table 4). Process models are detailed models that attempt to represent any known process through representative algorithms, while empirical models use a shortcut from an input to the desired output by using a factor (or fraction) approach. The choice is primarily driven by the data requirements for the respective models (site-specific simulations are more suited to process models), as well as by the scope of the simulation and the capabilities of the model, the intended output. The prospective model user plays a determining role in making this choice.

Table 4: Summary of current models used to estimate GHG emissions for the National Inventory Report, their strengths and limitations

Model	Year	Strengths and Uses Scope, Capability, Intended Output	Limitations
Process Models			
DeNitificationDeComposition (DNDC)	1992	The DNDC model focuses on nitrogen cycling and N_2O emissions, but also includes carbon change.	Testing and developing DNDC algorithms are a work in progress and require constant updated assessments in order to account for more farm practices. There is no documentation or version control. It is mainly for scientific use.
Century	1994	The Century model was developed to estimate carbon stocks and carbon change over the time scale of centuries.	Century has a long spin-up period and monthly timesteps. It focuses on carbon. Currently less in use and is mainly for scientific use.
DayCent	1998	DayCent is a daily time step version of the Century model. It simulates soil carbon, nitrogen cycling and GHG emissions.	DayCent's development appears to have been discontinued. Scientific use only.
Simulateur mulTIdisciplinaire pour les Cultures Standards (STICS)	1998	The STICS model focuses on crop growth and nitrogen losses, lately incorporating N_2O losses. It incorporates different cropping practices. Its development is ongoing.	The STICS model does not consider long term changes. It is primarily for scientific use.
Introductory Carbon Balance Model (ICBM)	1997	ICBM is a straight carbon model. It is extensively tested and user friendly.	ICBM's development is sporadic development. There is no version control. Primarily for scientific use.
Integrated Farm Systems Model (IFSM)	2018	IFSM simulates whole farm systems in the USA, specializing in dairy and beef production system. It includes whole farm economics.	IFSM has limited flexibility to system definition. It is not easily extendable to different production systems. There is limited information on underlying assumptions. Mainly for scientific use.
Empirical Models			
Holos Model	2008	Holos uses National Inventory factors to calculate whole-farm emissions, and is designed for ease of use. It accounts for all livestock producton and most crop types and systems. Upstream emission estimates are incorporated which allows this model to predict production system emission intensities and efficiencies.	The Holos model is Canada specific. It is limited to practices that are considered in the National Inventory.
		Example: HOLOS is user friendly and relates emission changes to changes in management practices. It is therefore of use to farmers as well as policy makers.	

Process models such as DayCent (Parton et al. 1998), DNDC (Li et al. 1992a, 1992b), as well as STICS (Brisson et al. 1998) have been used over the past two decades to simulate Canadian cropping systems, their productivity and impact on the environment (Guest et al. 2017; Jing et al. 2017; Grant et al. 2016; Morissette et al. 2016; Smith et al. 2013). One of the main objectives of these models is to estimate N_2O emissions from cropping systems, starting with the local scale (Smith et al. 2002, 2008), but with the goal to upscale to regional and national assessments (Smith et al. 2013; Grant et al. 2004). However, testing and developing N_2O algorithms in these models are a work in progress (Pattey et al. 2018; Kariyapperuma et al. 2011), thus potentially making previous assessments obsolete and requiring new and updated assessments.

The same models are also being used to estimate soil carbon change (Grant et al. 2016; Congreves et al. 2015; Smith et al. 2012), but there is a tendency to use different models for this particular purpose. Soil carbon change signifies the additional storage or loss of carbon in (or from) agricultural soils by altering the balance of carbon inputs (e.g., crop residues, manure) and carbon outputs (e.g., soil respiration). Calculating soil carbon change is important since in order to minimize climate change there is an incentive to promote gains in soil carbon. In some jurisdictions, soil carbon gains can be used as offsets for GHG emissions. Both Century (Parton et al. 1994) and ICBM (Andrén and Kätterer 1997) have been tested for use in Canada and have been upscaled to national assessments (Bolinder et al. 2006, 2008; Smith et al. 1997, 2001a), but the results of this research are meant for a rather scientific audience. In order to translate these scientific results to local, regional and national policy measures, process models have been used to establish applicable factors and indicators in policy assessments. For instance, the Century model was used to derive management-driven soil carbon change factors (Smith et al. 2001b) which were subsequently incorporated into the NIR, and the DNDC model was used to derive soil management changes to control levels of N_2O emissions (Smith et al. 2010).

Despite these successful applications, process models are still under development for different model components, as seen with DNDC (He et al. 2019; Congreves et al. 2016; Dutta et al. 2016; Kröbel et al. 2011) and STICS models (Jing et al. 2017; Morissette et al. 2016; Jégo et al. 2012). Complications arise when different versions of the same model are developed with updated model components and it is not always clear which model version was used. Additionally, all models presented so far focus on annual crops, with DNDC and STICS being now developed for perennial crops. Nevertheless, these models do not represent livestock production and its management practices.

This is different in the Integrated Farm Systems Model (Rotz et al. 2018) which was developed to simulate whole farm systems in the U.S., including cattle and dairy farms. This model has been applied multiple times in the Canadian context (Cordeiro et al. 2019; Duchemin et al. 2019; Thivierge et al. 2017; Alemu et al. 2015), but its application in the Canadian prairies (where approximately 80 per cent of Canadian agricultural land is located) is still outstanding; no upscaling work has been attempted and other livestock types have yet to be included.

The Holos model (Little et al. 2008) does include all livestock and major crop types by using algorithms (Tier 1 and Tier 2) developed by the Intergovernmental Panel on Climate Change (IPCC). This model aims to cover the vast majority of Canadian agriculture by using internationally acknowledged emission factors and easily obtainable input parameters. It does not provide estimates of productivity (such as crop yield and animal weight gain) but does account for productivity changes. The model further incorporates upstream emission estimates (emissions associated with the production of agricultural inputs), thus permitting the calculation of production system emission intensities and efficiencies (McGeough et al. 2012; Beauchemin et al. 2010). The easily obtainable input parameters permit upscaling to national scale while maintaining regional specifics (Legesse et al. 2016). Moreover, the model results can directly be related to changes in management practices (Alemu et al. 2017, Guyader et al. 2017), which emphasizes the intent for the model to be applicable to farmers and policy-makers alongside scientists.

It is worthwhile noting, however, that each model can be used in the context of other assessments (see, for instance, Sanscartier et al. 2014), depending on the assessment's purpose and data requirements. Most regional and nationwide assessments are hindered by the lack of detailed farm activity data rather than the lack of applicable models, even though the input parameters requirements of some models are not easily populated outside the setting of scientific experiments.

SUMMARY AND CONCLUSIONS

Of the 729 Mt of CO_2 eq emitted by GHGs in Canada in 2018, 59 Mt were emitted that year by the Canadian agricultural sector in the form of CO_2, N_2O and CH_4. The largest GHG emissions come from CH_4 through enteric fermentation (24 Mt of CO_2 eq) of beef and dairy cattle. Most N_2O emissions come from agricultural soils (25 Mt of CO_2 eq) through direct and indirect releases into the atmosphere. Major direct N_2O emissions occur during synthetic and organic nitrogen fertilizer applications, biomass decomposition, soil cultivation and conservation tillage, mineralization of soil organic matter, summer fallow, irrigation and manure on pasture, range or paddock. Handling and storing livestock manure emits indirect CH_4 and N_2O, and the amounts vary depending on the quantity of manure handled, its characteristics and the type of manure management system used. In 2018, manure management was the source of 7.9 Mt of CO_2 eq emitted as both CH_4 and N_2O. Carbon dioxide was also emitted after lime and urea applications as well as with the use of fossil fuel combustion machinery.

Field techniques and empirical and process models have been developed to estimate and validate GHG emissions for different farm scenarios. The process is complicated as these models aim to simulate every component of a farming system, whether a large beef cattle operation or a small animal and crop farm. Consequently, the models are constantly being assessed and revised as more data are available and methodologies are improved.

As we gain better understanding of GHG emission estimates for different farm scenarios and the largest sources of GHG emissions, the next step is to target these sources and find ways to decrease them while maintaining or improving the farm's financial sustainability. Changes will not be made if they are not cost effective and if they do not bring a positive change to a farmer's busy life. Policies to reduce GHG emissions are being introduced across Canada, but are they being adopted? Are they adequate? How do farmers find out about them? What are the incentives? These questions will be discussed in a follow-up article.

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APPENDIX

I. INDIVIDUAL LOCAL MEASURES: ON-FARM MANAGEMENT

1. CROPPING SYSTEMS AND CARBON SEQUESTRATION

Increasing soil carbon content and storing it either in the soil or in plants is one measure to reduce CO_2 losses to the atmosphere. This is achieved by keeping the soil covered using either cover crops or mulches, converting annual cropping to perennial cropping (VandenBygaart et al. 2010) and minimizing traffic on the soil surface. No-till practices allow the soil structure to develop its natural porosity, soil moisture retention, crop residue retention and the buildup of organic matter which stores carbon and creates a healthy and nutritious environment for plant roots, thereby improving productivity (Liang et al. 2020, May et al. 2020).

Gan et al. (2014) found that improved farm practices in a semi-arid environment lowered the carbon footprint of wheat, reaching an average of -256 kg CO_2 eq ha^{-1} per year. The main changes consisted in applying fertilizers on the basis of soil tests, reducing the frequency of summer-fallow rotations and rotating cereals with legumes. This enabled the wheat crop to take up more CO_2 from the atmosphere than it emitted during its production.

To achieve a decline in the intensity of GHG emissions in Canadian agriculture, Agriculture and Agri-Food Canada is developing an emission-intensity metric that will represent emissions from the growth, transportation and processing of one unit of a given product such as a tonne of grain or a kg of beef (Agriculture and Agri-Food Canada 2020).

2. LIVESTOCK AND MANURE MANAGEMENT

Intensively managed grazing land is likely to be a net GHG source, including CH_4 emissions from grazing beef and dairy cattle and N_2O emissions from manure or fertilized pastures (Carbutt et al. 2017). Global methane emissions have been rising rapidly since 2007 and about half of this rise comes from increasing numbers of ruminant livestock (Nisbet et al. 2019). However, in Canada, declining animal populations have resulted in declining CH_4 emissions between 2006 and 2011. Dairy cow populations in Canada declined from 1.8 to one million head, and this did not affect total milk production. Beef cattle populations decreased about 14 per cent since 2006 due to a challenging economic environment such as diseases (bovine spongiform encephalopathy crisis in 2003–2004), country-of-origin labelling and a high Canadian dollar that made exports to the U.S. more expensive (Agriculture and Agri-Food Canada 2020).

For large livestock operations, managing manure emissions by capturing CH_4 to generate heat and electricity is a viable option. The energy produced through biogas generation systems and trading of renewable energy certificates render this a profitable solution (Green 2020). Another solution addresses manure piles: by aerating them, denitrification is stalled and N_2O emissions are reduced. In addition, adding urease inhibitors to manure piles reduces the conversion rate from urea to N_2O (Government of Western Australia 2020).

3. FARM EQUIPMENT MANAGEMENT

Numerous options exist to create synergies between management of agriculture, vegetation and soils to reverse degradation. Sustainable land management practices include reduced tillage, residue retention, use of nitrogen-fixing cover crops or intercropping, and managing mixed-species and uneven-aged forests. These practices aim to halt erosion and include avoiding clear-cutting, contour plowing and strip cropping, along with the use of organic amendments such as mulches, compost and biochar to increase soil carbon and nutrient content (Olsson et al. 2019). These practices also allow a safer management of agricultural lands by reducing energy consumption from agricultural equipment and thereby reducing CO_2 emissions.

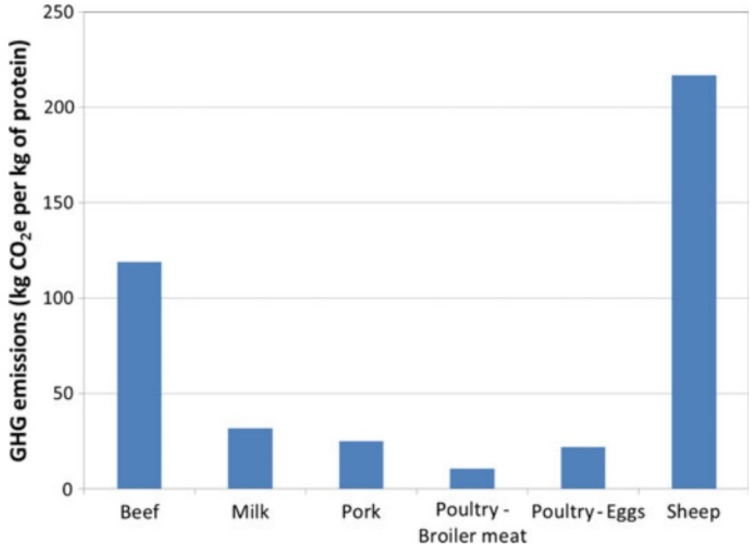
4. OTHER METHODS

There are various options for reducing GHG emissions from agricultural practices. Kroebel et al. (2013) describe in detail the workings of the HOLOS model which aims to consider every aspect of a whole-farm system and the associated GHG emissions. It allows producers to explore different soil, crop, fertilizer/manure and pest management options for reducing on-farm GHG emissions.

II. INDIVIDUAL LOCAL MEASURES: HOME FOOD CHOICES

It is complicated to estimate and compare GHG emissions from livestock operations that produce different products (beef, pork, dairy, poultry and sheep) using different production systems. Using protein as a common denominator creates comparable measurements from each livestock commodity. Dyer and Desjardins coined the term “GHG-protein indicator” as a tool for comparison in 2010 and emissions per kg of protein were calculated using data for 2001 (Fig. 8).

Figure 9: GHG emissions per kg of protein for livestock products in Canada in 2001 (Dyer et al. 2010)



Protein produced from sheep and beef production had higher GHG emissions than from other livestock commodities in Canada in 2001 (Fig. 9). Both sheep and beef have lower fecundity rates and produce higher CH_4 emissions during digestion than other livestock commodities. Using the protein indicator, Dyer and Desjardins (2020) investigated the impact of reducing red meat consumption on GHG emissions in Canada. They state that by eating less red meat and diversifying meat choices, consumers “could significantly reduce GHG emissions from agriculture.”

Vergé et al. (2018) argue that using an integrated approach that considers multiple agricultural sectors as complementary will reduce environmental impacts and render agricultural production more sustainable. For instance, considering the dairy and beef industries as complementary meat-production sectors, they evaluated the Western Canada beef industry (mainly beef production) and the Eastern Canada combined beef and dairy industry (about 50/50) using the Unified Livestock Industry and Crop Emissions Estimation System. They found that integrating both dairy and beef production within one system resulted in a 22 per cent lower carbon footprint of meat compared to meat only being produced by the beef industry. A simulation in which Western Canadian beef production was integrated with equal size dairy populations resulted in a 31 per cent fewer emissions than current levels in Western Canada. According to this study, there is an opportunity to reduce the environmental impacts of agricultural production systems by increasing production efficiencies through multi-product production systems compared to single-product systems.

About the Authors

Dr. Fouli grew up in Tunisia where she studied georesources and environmental engineering. She later attended graduate school in Scotland and in the USA where she taught and conducted research in soil science. She continued with research in nutrient management and animal farming in Maryland and Saskatchewan, and later joined a consulting firm in Alberta as an environmental scientist and project manager. She currently consults independently on water and soil quality, watershed management, and climate change.

Dr. Hurlbert's research focuses on governance and climate change, energy and water; interrogating laws, policies and practices that will address both the problem of climate change and adaptation, and mitigation to the changing climate. She has participated in and led research projects focusing on aspects of governance including energy, water, agricultural producer livelihoods, drought, and flood. Hurlbert also serves as a Coordinating Lead Author, Contributing Author and Review Editor for the Intergovernmental Panel for Climate Change.

Dr. Kröbel hails from Germany and has a BSc in Organic Farming. He switched direction to Environmental Systems Analysis for his MSc, only to return to agriculture with his PhD which focused on simulating greenhouse gas emissions. Since then, he has been leading the Holos model science program, a software application developed for Canadian farmers to test the influence of their management choices on their farm's greenhouse gas budget.

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The School of Public Policy
University of Calgary, Downtown Campus
906 8th Avenue S.W., 5th Floor
Calgary, Alberta T2P 1H9
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