International Journal of
Environmental Sciences & Natural Resources
ISSN: 2572-1119

Juniper Publishers
key to the Researchers

Review Article
Volume 32 Issue 3 - June 2023
DOI: 10.19080/IJESNR.2023.32.556338

Int J Environ Sci Nat Res

Agricultural Greenhouse Gas Emissions and Mitigation Strategies for Promoting Sustainable Agroecosystems in Canada – A Review

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Submission: May 31, 2023; **Published:** June 16, 2023

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Abstract

Canada's agricultural greenhouse gas emissions are ~73Mt CO_2eq yr^{-1} (10% of the total), which importantly includes 29% and 78% of the total CH_4 and N_2O emissions, respectively. These emissions are caused by enteric fermentation ~24Mt, manure management ~8Mt, agricultural soils/crop production ~24Mt, and on-farm fuel use ~14Mt. Canada has committed under the Paris Agreement-2015 to reduce its total emissions by 30% below the 2005 levels by 2030, whereas its Emission Reduction Plan (ERP)-2030 of $9.1 billion targets a 40-45% reduction; and become a net-zero country by 2050. The ERP-2030 envisages reducing agricultural emissions by 19Mt CO_2eq yr^{-1} by increasing carbon sequestration ($780 million) from wetlands, peatlands, and grasslands; implementing beneficial management practices (BMPs); and reducing fertilizer use. It is a challenging task as agricultural emissions have been stable during the last couple of decades, whereas food and fiber requirements are growing. Nevertheless, as rightly perceived in the ERP, the agriculture sector is unique in reducing net emissions either by decreasing emissions or increasing sequestration through BMPs. Furthermore, the ERP will provide subsidies to the farmers (~$900 million) to adopt sustainable practices and use more energy-efficient equipment while supporting research and knowledge transfer. The subsidies would help address some of the monetary barriers producers face in adopting these practices and technologies, leaving behind the associated social and technical challenges. It is, therefore, important to follow the "observe, evaluate, and improve" strategy for better implementation of the ERP-2030 and better achieve its targets and objectives.

Keywords: GHG; Emission reduction plan; BMP; Agricultural emissions; Canada

Introduction

Global greenhouse gas (GHG) emissions continue to increase over time and have touched an unprecedented figure of ~50Gt of CO_2eq yr^{-1} in 2020 [1]. The major emitting sectors are energy, industry, transport, buildings, and agriculture (including cropping, forestry, livestock, and other land use), which respectively contribute around 35%, 21%, 14%, 6%, and 24% to the total emissions [2]. These emissions over the years have caused a substantial increase in the atmospheric concentrations of the three major GHGs, i.e., Carbon dioxide (CO_2), Methane (CH_4) and Nitrous oxide (N_2O) up to 415ppm, 1908ppb, and 334ppb, respectively, which are 149%, 262%, and 124% of its pre-industrial levels [3]. These are long-lived GHGs, which along with water vapors, change the earth's atmospheric energy balance (expressed as Wm^{-2}) to cause warming and associated climatic changes [4].

There are a few other GHGs, namely Chlorofluorocarbon (CFCs), Hydrofluorocarbon (HFCs), Perfluorocarbons (PFCs), and Sulfur hexafluorides (SF_6s). These GHGs are entirely human-induced but are no longer a significant concern despite having a higher Global Warming Potential (GWP/expressed in CO_2eq), as shown in Table 1, as their atmospheric concentrations continuously decline due to better management [5]. Control of these GHGs has been seen as a global success story. Whose journey started in 1974 when scientists warned about the dangers of these gases and their potential to destroy the ozone layer, which protects humans and plants from dangerous ultraviolet (UV) radiation and has a very high global warming potential. Through rigorous scientific research and international cooperation, the Montreal Protocol was established in 1987, ultimately leading to the phase-out of 98% ozone-depleting chemicals and the ozone layer's recovery by 2065. This shows how scientific vigilance, public policy, and citizen action can protect the environment for future generations [6].

Table 1: Global Warming Potential of GHGs [7].

GHG	Global Warming Potential (CO_2eq)
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296
Chlorofluorocarbon (CFC)	5,700–11,900
Hydrofluorocarbon (HFC)	120–12,000
Sulfur hexafluorides (SF_6)	22,200

As per the success of the Montreal Protocol, the United Nations Framework Convention on Climate Change (UNFCCC) developed a worldly consensus to limit GHG emissions for a sustainable world. Therefore, under its Paris Agreement of 2015, almost 195 countries pledged to reduce their GHG emissions. The objective is to check the rise in average global temperature to well below 2°C than the pre-industrial levels by 2100 [8]. This means stabilizing atmospheric GHGs to ~450ppm CO_2eq by then. Researchers call it overambitious, but the agreement is somewhat helping as the fossil fuel-oriented emissions have been stable since 2015 to ~36Gt CO_2-$_{Eq}$ yr^{-1}, even though overall emissions continue to increase [9,10]. The pathway to reduced emissions encompasses all the sectors, including the energy sector, which is mainly contributed by the coal-fired power plants [11]; the transportation sector includes all kinds of land, water, and air travel, whereas building and industrial emissions are primarily caused in producing metals, chemicals, cement, etc. Most of these industrial processes are inefficient and offer much potential for quickly reducing GHG emissions. However, it is challenging to rapidly cut those emissions due to social and economic factors [12,13].

The agriculture sector, which includes Agriculture, Forestry, and Land Use (AFOLU), is a major source of GHG emissions contributing around 24% (~10-12Gt CO_2eq yr^{-1}) to global emissions. However, it takes back around 1/5th of its contribution through carbon sequestration [2]. Particularly its contribution to the non-CO_2 GHGs is significant, i.e., ~56% of the total emissions [14], which enhances its mitigation potential. The agricultural emissions are caused mainly by deforestation, livestock, soils, crop production, and nutrient management. Almost half of those are contributed by deforestation or land use changes, while the rest are from agriculture and livestock production. In contrast to the other sectors, agriculture offers a unique opportunity to reduce the net GHGs by decreasing emissions or increasing sequestration through Best Management Practices (BMPs). That is why more than 100 countries voluntarily pledged to reduce agricultural emissions in the 2015 Paris Agreement. Nevertheless, this task is quite challenging as it is related to food, feed, and timber production, which are the primary requirements of the increasing worldly population and involve millions of actors on a globally limited land area with multiple competing demands [2].

Canada's contribution to global GHG emissions is less than 2%, despite being the 4th largest energy producer [14-16]. Total GHG emissions remained at 730Mt CO_2eq yr^{-1} in 2019, as detailed in Table 2. The emissions have been relatively consistent and have slightly declined (~1%) than 2005 levels. The emissions during 2005-2020 increased in the oil, gas, and transport sectors and considerably decreased in the electricity and heavy industry sectors, whereas agricultural emissions have been relatively consistent at ~73Mt CO_2eq.

Table 2: Relative contribution of the GHGs to the total emissions in Canada [15].

GHG	Emissions (Mt CO_2eq)
Carbon dioxide (CO_2)	580
Methane (CH_4)	98
Nitrous oxide (N_2O)	37
Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur hexafluorides (SF_6), and Nitrogen Trifluoride (NF_3)	13
Total	**730**

It is evident from the table that about 80% of total emissions are from the combustion of fossil fuels producing CO_2; the CH_4 (13%) emissions are mainly from oil and gas systems, agriculture, and landfills, and N_2O emissions (5%) are contributed by agricultural soil management and transport [15]. Despite optimistically being a lower emitter globally, Canada is one of the highest per capita

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emitters, i.e., 19.4 tons CO_2eq capita^{-1} yr^{-1} against a global average of 4.69, which has to go down to 1.7 by 2050. Nevertheless, Canada's emissions have decreased since 2005, when it was 22.9CO_2eq capita^{-1} yr^{-1}. There is much interprovincial diversity, as residents of Saskatchewan and Alberta produce ~68tons CO_2eq capita^{-1} yr^{-1}. In contrast, those in British Columbia, Ontario, and Quebec produce 10-14 tons CO_2eq capita^{-1} yr^{-1} [17]. This provides a unique margin and opportunity to decrease emissions and simultaneously achieve other socioeconomic development goals.

Canada has accordingly launched its Emissions Reduction Plan (ERP) to reduce emissions by 40-45% below 2005 levels by 2030 and reach net-zero emissions by 2050. The plan includes an investment of $9.1 billion, which includes $900 million for the farmers to adopt sustainable practices and use more energy-efficient equipment while supporting research and knowledge transfer [18]. On a broader scale, the plan requires reducing agricultural GHG emissions to almost half in the next 7 years. Whereas historically, those emissions have been consistent since 2005. Therefore, it is a challenging task, requiring an in-depth analysis of the viable options and opportunities that can reduce emissions or increase carbon sequestration. The paper investigates the possibilities and opportunities, and challenges to implement those, along with some policy guidelines. This will help achieve the targets of the ERP-2030 and net zero by 2050s for sustainable development of Canada.

Estimating GHG Emissions in Agroecosystem

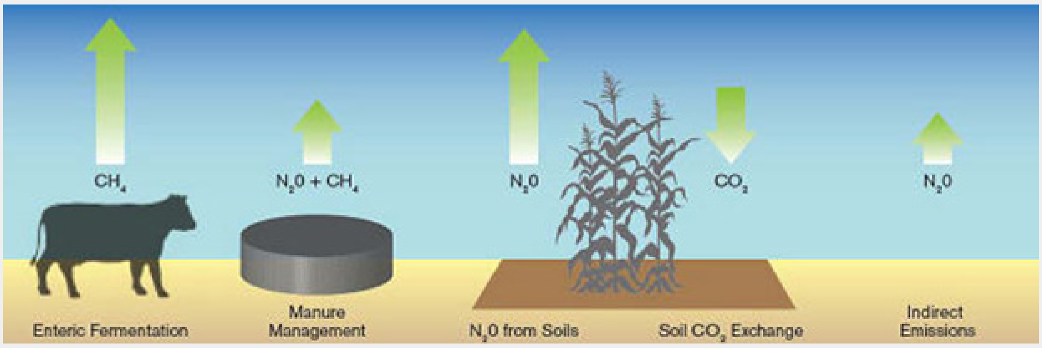

Figure 1: A schematic of GHG emissions/sequestration in a typical agricultural system [20].

Agricultural emissions include CO_2, CH_4, and N_2O. However, it can also serve as a sink for CO_2 through carbon sequestration in biomass and soil, as shown in Figure 1. The methods used to estimate these GHGs in Canada are mostly based on IPCC Guidelines (2006) [19], as detailed in the subsequent sections. The GHG emissions data presented herein are based on the Government of Canada statistics, based on the IPCC (2006) methodologies and guidelines, which encourage using country-specific refined methods and complex modeling approaches. The statistics are annually inventoried and maintained by the Pollutant Inventories and Reporting Division of Environment and Climate Change Canada (ECCC). The reporting threshold has been set at 50-kilo tonnes CO_2eq/year. All facilities that meet or exceed this threshold must submit their annual emissions data to the ECCC by 1st June of the following year [21]. Furthermore, the IPCC (2006) recommends that efforts to quantify GHG emissions should be prioritized based on the level of importance of each source [19]. This means that the most effort should be focused on quantifying emissions from critical sources, such as those which (i) contribute the most to the overall emissions inventory in terms of quantity, (ii) have the most significant potential to increase or decrease emissions levels over time, and (iii) have the highest level of uncertainty associated with them. The prioritization ensures effective utilization of resources and accurate quantification of emissions at the national level for the sources that significantly impact the climate [21].

Among agricultural emissions, **Enteric fermentation** is a critical contributor, i.e., CH_4 produced by animals during the digestion of food. Such emissions are estimated by multiplying the animal population of each category/subcategory by its corresponding regionally derived emission factor. For cattle, the IPCC Tier 2 methodology is used, which integrates data on production stages, physiological status, diet, age class, sex, weight, growth rate, activity level, and production environment. For non-cattle animals, that is, swine and sheep, estimates are based on IPCC Tier 1 methodology [19], and similarly for other animals like poultry, rabbits, and fur-bearing animals. The animal population data are ascertained province-wise for each category/subcategory from Statistics Canada [22], whereas data for each production stage are obtained through surveys of beef and dairy cattle specialists nationwide [15].

Manure management refers to emissions related to handling large quantities of liquid and solid animal waste, storage, and

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handling. Both CH_4 and N_2O are emitted therein. The emissions depend on the quantity of manure handling, moisture and nutrient contents, and the management system. Soon after the excretion, its decomposition starts, producing CO_2 under well-aerated conditions and CH_4 under poor aeration. The CH_4 emissions are calculated using IPCC Tier 2 methodology [19], multiplying the respective populations with the corresponding emission factor for each animal category, just like enteric fermentation [23-25]. The N_2O emissions occur due to nitrification and denitrification of nitrogen contained in the manure. For dairy cattle, nitrogen excretion is calculated using the mass balance approach provided in the IPCC Tier 2 methodology, based on feed intake, crude protein in the diet, and milk production. And the N_2O emissions by multiplying the animal population with the nitrogen excretion rates and the respective emission factors based on the manure management system. At the same time, IPCC Tier 1 emission factors are used for minor animals [15].

Agricultural soils are a source of N_2O emissions, and some CH_4; N_2O emissions occur directly and indirectly. Direct sources include the application of organic and inorganic fertilizers, crop residue decomposition, organic matter mineralization, and cultivation of organic soils. Indirect sources include nitrogen volatilization from inorganic fertilizer and manure, leaching, runoff, manure, and crop residue burning, and changes in crop rotations and management practices. Nevertheless, the application of organic/inorganic fertilizers is the single largest source of emission in this category. Fertilizers mainly emit N_2O; the added nitrogen from fertilizers undergoes nitrification and denitrification in the soils, releasing N_2O into the atmosphere [26]. However, its emission rates depend on various factors, such as soil types, climate, topography, farming practices, and environmental conditions. Therefore, regionally-derived emission factors are used per IPCC's (2006) Tier 2 methodology [19]. This considers local conditions such as moisture regimes and topographic conditions at the eco-district level of Canada. The estimates are then scaled up to provincial and national levels. To estimate the amount of nitrogen applied to the land, yearly fertilizer sales are used, assuming that all the sold fertilizers are applied for crop production [27,28]. The other minor N_2O emissions/removals come from tillage practices, summer fallow, and irrigation. Burning of agricultural residue and application of urea-containing fertilizers have minimal contribution to agricultural emissions and has therefore been excluded.

The **on-farm fuel use** is a major component of agricultural emissions. The IPCC Tier 3 approach is used to estimate emissions from off-road (on-farm) vehicles and equipment used on farms. Canada-specific emission factors are used, which are multiplied by activity data in terms of the number of vehicles or equipment, their usage patterns, and other relevant parameters. The emissions estimates are more accurate than those obtained using Tier 1 or Tier 2 methods, as they consider more detailed information on the specific types and uses of equipment and other factors that can affect emissions [19]. Further refinements are underway to rationalize the estimates further [15].

Land Use, Land Use Change, and Forestry (LULUCF) is a high-priority sector, having the potential to be a net sequester of GHGs. However, it is not accounted for in the national totals due to higher uncertainties. It has six subgroups, of which forests, croplands, and grasslands serve as carbon sinks, whereas wetlands, settlements, and harvested woods contribute to emissions. It is reported by the Canadian Forest Service of Natural Resources Canada (NRCan/CFS) and Agriculture and Agri-Food Canada (AAFC). NRCan/CFS gathers data and delivers estimates of GHG emissions/removals based on the forest land (the afforested and deforested land during the year is duly accounted for) and harvested wood products. Canadian-specific factors are used for the estimates. For instance, for Canadian boreal forests ~300 million ha, carbon sequestration rates: 0.4-1.2 tonnes CO_2eq ha^{-1} yr^{-1} [29-33] are used. To estimate emissions from harvested wood products, it considers various end-uses and effects and calculates the amount of carbon released over time. These methods use assumptions about the typical lifespan of different wood products and the rate at which carbon is released over time; therefore, this involves uncertainties. The proportional contribution of grasslands, wetlands, and settlements is minimal, ranging from 0.05-2.6Mt CO_2eq yr^{-1}, and therefore excluded [34].

AAFC is responsible for delivering estimates of GHG emissions/removals from cropland or crop production, including management practices' effect on agricultural soils and the residual impact of land conversion to cropland soils. It uses different process-based models, such as DNDC (Denitrification-Decomposition), that simulate data on soil, climate, vegetation, plant residues, soil texture, temperature, moisture, and different management practices, such as crop rotations, tillage, and fertilization [35]. ECCC manages and coordinates all other LULUCF estimates, undertakes cross-cutting quality control and quality assurance, and ensures the consistency of land-based estimates through an integrated land representation system [15].

Agricultural emissions in Canada have been stable over the last few decades, along with intra-sectoral variations. It is, therefore, challenging to cut it to half in the next 7 years, as envisaged in the ERP-2030. Nevertheless, proper conservation and management practices can make a difference. The results and Discussion section presents an overview of the emissions fluctuations in each subsector from 1990-2020, along with a discussion on the underlying factors of the variations to serve as benchmarks. The information has been presented subsector-wise along with mitigation strategies per Canada's ERP-2030, challenges in availing of those, recommendations, and guidelines [18].

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The Emissions Dynamics and Mitigation Strategies

Canada's agricultural sector provides food for its inhabitants and exports it to other parts of the world. It contributes around $143 billion to its GDP (7.2%) and nearly $15 billion to the trade surplus [18]. It contributes ~10% to the total GHG emissions (Figure 2), which becomes around 73Mt CO_2eq yr^{-1}, of which animal production contributes (36Mt) majorly including enteric fermentation ~24Mt and manure management ~8Mt; crop production/agricultural soils ~24Mt, and on-farm fuel use ~14Mt. Importantly, the sector contributes 29% of the total CH_4 emissions and 78% of the N_2O emissions [15].

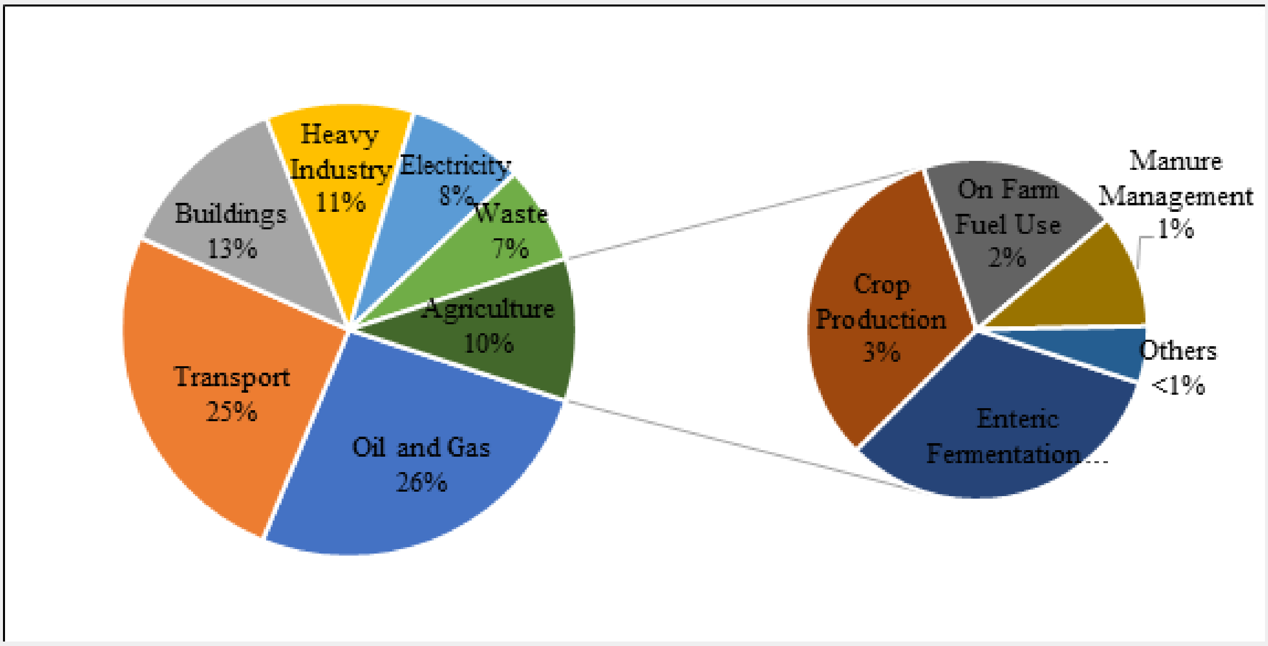

Figure 2: Sectoral contributions to Canada's GHG emissions in 2019 [15].

Proportionately, the agriculture sector contributes somewhat more to GHG emissions than its GDP contribution. Nevertheless, a historical perspective of the sector is promising, as the GHG emissions have been consistent despite growth over the last couple of decades. This contrasts the previous estimates, where a business-as-usual scenario projected them to rise above 100Mt CO_2eq yr^{-1} by now. And significant reductions were recommended to fulfill the Canadian government's commitment to the Kyoto Protocol [36].

Agricultural GHG emissions can be reduced either by increasing soil carbon sequestration or by decreasing the emissions in livestock and crop production [5]. Agricultural soils in Canada (62 million ha) sequestered ~4Mt CO_2Eq in 2019, offsetting approximately 6% of total annual agricultural emissions [15]. The management practices for GHG reduction include livestock management in terms of adjusting/switching feeding, breeding, and manure management, changing land use and crop management by adopting/switching to reduced tillage, planting cover crops, switching to renewable energy sources such as solar or wind in farming, reducing food waste, improving fertilizer and nutrient management by using precision agriculture technologies, etc. [37-41]. Overall, reducing agricultural GHG emissions requires a combination of changes in agricultural practices, technological advancements, and policy interventions [42]. However, these options cannot currently be recommended as their socio-economic aspects have not been fully evaluated, and there are still uncertainties in the emission estimates. It is evident from the Figure 3 that Atlantic Canada's contribution to the emissions is minimal, as most of the agriculture is concentrated across the Prairies, Quebec, and Southern Ontario.

Enteric fermentation

Globally, the livestock sector contributes about 14.5% to the total emissions [43]. The enteric fermentation in ruminants emits CH_4, significantly contributing to the agricultural GHGs and total emissions. About 3-12% of their consumed diet is converted to CH_4 and released into the atmosphere. Methane is produced in the ruminants' rumen by microorganisms called methanogens as a by-product of their digestive and metabolic processes [44]. In Canada, these emissions can be subdivided into cattle (cows), sheep, swine, and other animals. However, about 96% come from cattle (beef and dairy cows) production, with beef cows being

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the major source [45]. The variations of the enteric fermentation emissions over time are shown in Figure 4. It is evident from the Figure 4 that the emissions increased by 7% from 1990 to 2020. However, a significant increase of ~40% occurred during 1990-2005, driven by high commodity prices, which had increased the population and weight of beef cattle. However, in 2003, an outbreak of Bovine Spongiform Encephalopathy (BSE), also known as mad cow disease, caused beef populations to decline sharply by 27% [46]. The dairy cow populations declined by 23% during 1990-2020, leading to a 13% decline in their respective emissions. Proportionately, the reduction in CH_4 emissions is lesser than the population decline. It is so because an average dairy cow now emits more CH_4 than in the 1990s, as it consumes more feed and produces more milk due to improved genetics and management [47]. Therefore, the emission reductions associated with the decline in the dairy population have been partly offset by more emissions per dairy cow.

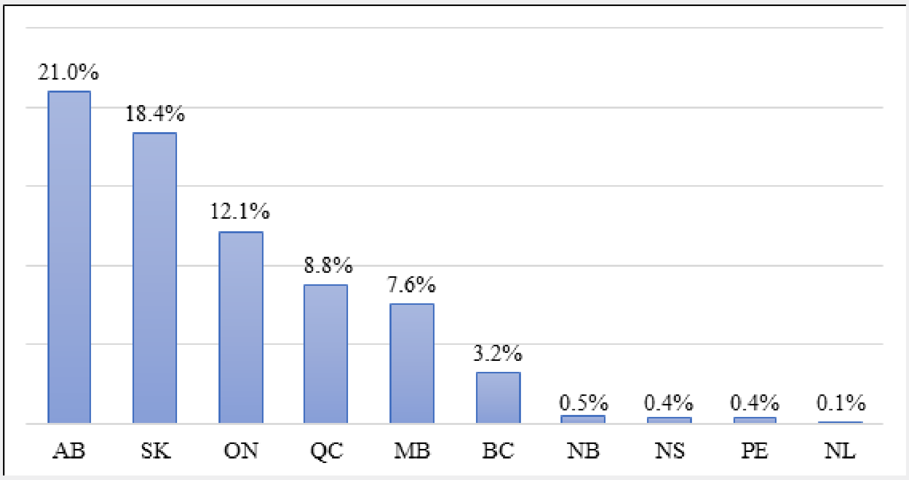

Figure 3: Relative contribution of provinces to the agricultural emissions.

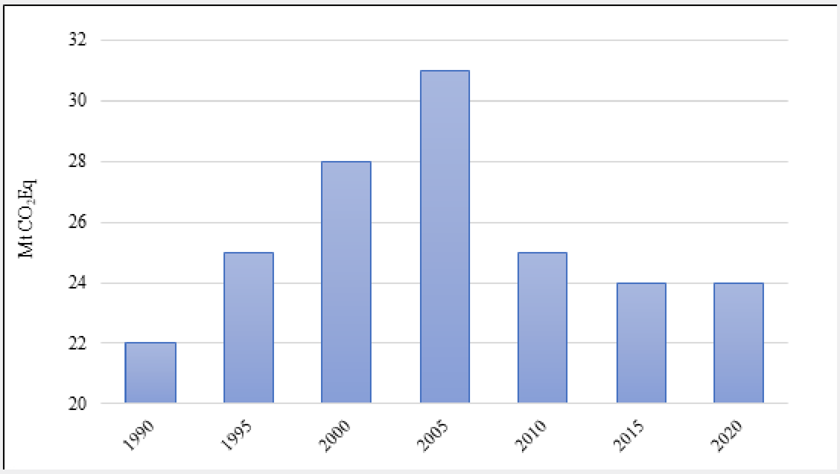

Figure 4: Temporal variations in the enteric fermentation emissions [15].

Reducing enteric CH_4 emissions is essential for mitigating climate change, improving the sustainability of livestock production systems, and meeting the increasing demand for animal products [48,49]. Different diets have been tested to inhibit cows' methanogen activity to reduce CH_4 emissions. Alternatively, hydrogen gas (H_2) production in the rumens is inhibited or redirected to reduce CH_4 emissions [44]. In this regard, supplementing barley silage-based diets with corn grain showed a minimal effect on beef cow emissions. Instead, maximizing feed intake above cows' maintenance energy requirements was found more effective in reducing the proportion of feed energy lost as CH_4 every day, thus reducing the number of days to market and

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associated CH_4 production thereof. Thus, feeding beef cows for maximum gain is an important CH_4 mitigation strategy that should be adopted by the industry [50]. For dairy cows, using ionophores, high-quality forages, and more grain feed also exhibited some promise to reduce CH_4 emissions by manipulating ruminal fermentation and inhibiting methanogens and protozoa. Besides, the addition of probiotics, acetogens, bacteriocins, archaeal viruses, organic acids, plant extracts, immunization, and genetic selection of cows, can also reduce the CH_4 emissions but require further research to validate their effectiveness [51].

The ERP-2030 has not specifically targeted reductions in this category, except identifying public concerns wherein it was proposed to reduce government subsidies for the meat and dairy industry and promote plant-based diets for Canadians [18]. Resources should have been allocated in the ERP-2030 towards the feasibilities of the abovementioned strategies and an economic incentive for the farmers to adopt proven management practices and diets to lower CH_4 emissions [18]. It was found that beef and milk producers can reduce their CH_4 emissions by 5-25% by adopting the abovesaid management practices [44] but at an added cost of production. Therefore, despite being technically feasible, they would not adopt such practices on economic grounds.

Manure management

Manure management refers to all activities, decisions, and components used to handle, store, and dispose of feces and urine from livestock to preserve and recycle its nutrients [19,52]. Manure management contributes approximately 7.9Mt CO_2eq yr^{-1}, which is ~10% of agricultural GHG emissions in Canada, both in terms of CH_4 and N_2O emissions [18]. About 10% of the agricultural CH_4 emissions and ~45% of the N_2O emissions are produced by manure management [53]. The CH_4 emissions come from the anaerobic decomposition of the manure during its storage, which is mostly released during handling and application, that is, transfer of manure from storage to application equipment, spreading or injection of manure into the soil, and mixing manure with other substances. In addition, CH_4 can also be produced during certain manure treatment processes [54]. The N_2O emissions also occur during manure storage and application. However, direct emissions of N_2O from manure storage are small as compared to CH_4 emissions. During manure storage, the nitrification process occurs in which some of the organic nitrogen is converted to NH_4^+ and then to nitrate NO_3^- releasing N_2O as a by-product. Additionally, when manure is applied to soils already saturated with nitrogen, excess nitrogen can be converted to N_2O through denitrification [55]. In manure-amended soils, most of the N_2O is produced through microbial nitrification under aerobic conditions and partial denitrification under anaerobic conditions, with denitrification generally producing a larger quantity [56] (Figure 5).

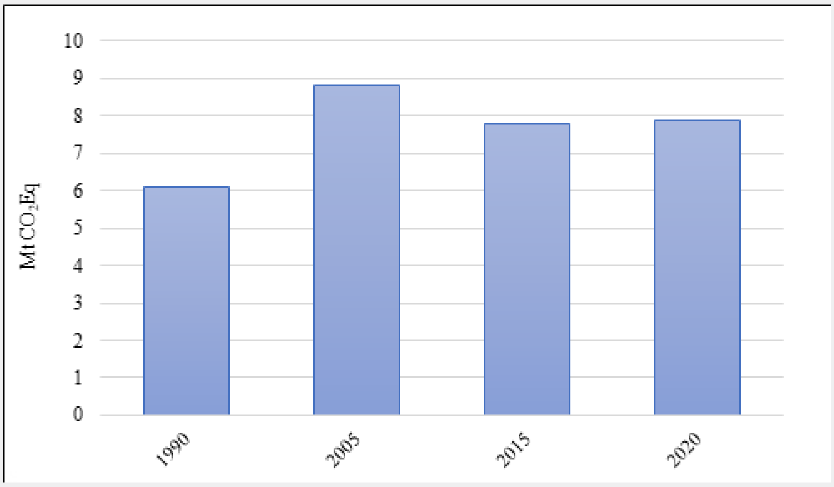

Figure 5: Temporal variations in manure management emissions [15].

It is evident from the Figure 5 that GHG emissions from manure management have been declining since 2005. It is due to the increased adoption of anaerobic digestion and other low-emission manure management practices, which reduced CH_4 emissions over the past few decades [57]. However, N_2O emissions have been more variable and are influenced by the type and quantity of manure, management practices, and environmental conditions [58]. The contribution of manure management to agricultural GHG emissions can vary depending on the specific management practices used. Implementing improved manure management practices, such as anaerobic digestion or composting, can help to reduce GHG emissions from manure management [59,60]. Some key strategies of Canada's Emissions Reduction Plan-2030 in manure management should be [61-64]:

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a) Developing codes of practice for manure management in collaboration with industry stakeholders that will provide guidance on best practices for reducing emissions and minimizing environmental impacts.

b) Encouraging the adoption of low-emission manure management practices such as anaerobic digestion and composting.

c) Precise application of manures through PA technologies to optimize application rates and reduce the risk of nitrogen losses through volatilization or leaching.

d) Supporting research and innovation to identify new and innovative approaches to reducing emissions from manures.

The ERP-2030 envisaged BMPs should include more researched and practical manure management strategies, encourage the adoption of these practices, and support research and innovation to achieve the envisaged targets [18].

Agricultural soils/crop production

Agricultural soils contribute ~24Mt CO_2eq yr^{-1} to agricultural emissions (~73Mt CO_2eq yr^{-1}) in Canada for crop production [18]. This includes emissions caused by applying organic and inorganic nitrogen fertilizers to soils and crop residue decomposition, with minor contributions from some other activities. Synthetic (inorganic) fertilizers contribute about 23% of agricultural emissions. Synthetic/inorganic fertilizers release nitrogen in a form that is easily accessible to plants but can also be easily lost to the atmosphere as N_2O [65]. Similarly, organic nitrogen sources such as manure and biosolids also contribute to emissions, as they contain high levels of nitrogen that can be released as N_2O and other GHGs during decomposition [66]. Other than that, crop residue decomposition, both above and below ground, produces CO_2 and N_2O [67]. The variations in the emissions of agricultural soils over time have been depicted in Figure 6.

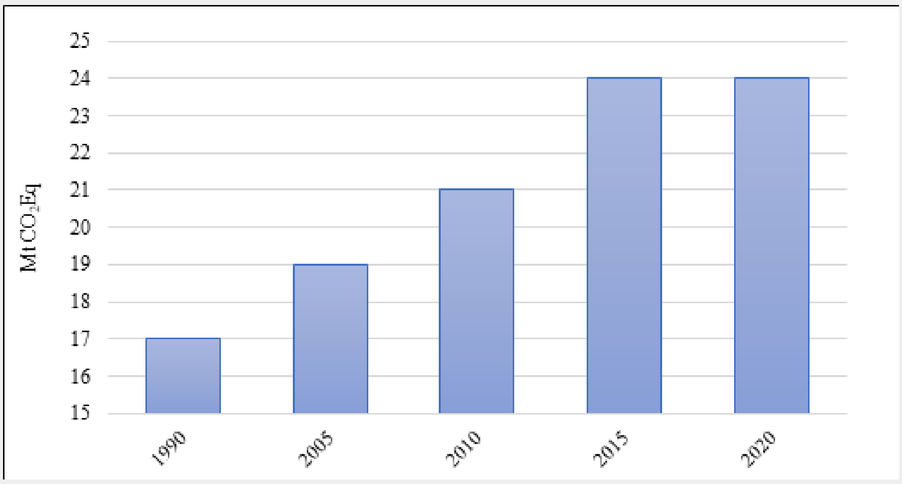

Figure 6: Temporal variations in agricultural soils emissions [15].

It is evident from the Figure 6 that agricultural soil emissions have gradually increased over time since 1990 but have been stable since 2015. The increase in emissions is mainly attributed to the rise in inorganic fertilizer use. Whose consumption steadily increased from 1.2Mt N to 2.6Mt N during 1990-2020, leading to a 98% increase in emissions, from 6.8 to 13Mt CO_2eq yr^{-1}. The increase in urea-based (carbon-containing) fertilizers also resulted in a 205% increase in emissions of CO_2 from soils. Whereas emissions from crop residue decomposition varied depending on weather conditions and crop yield, ranging from 3.3 in 2002 to 6.5Mt CO_2eq yr^{-1} in 2017 [68].

The ERP-2030 has set a GHG reduction target of 19Mt CO_2eq yr^{-1} in the agriculture sector by increasing carbon sequestration from wetlands, and grasslands, beneficial management practices, wherein the reduction in fertilizer use is anticipated to translate into a decrease of approximately 4Mt CO_2eq yr^{-1} (~1/3rd of the current contribution), that is, 30% below 2020 levels by 2030 [18]. It is a challenging task, particularly against rising food demands and prices. However, crop management practices can significantly reduce emissions from agricultural soils [69]. The following strategies can be used to reduce emissions from agricultural soils [70-76]:

a) Adjusting fertilizer application rates based on crop and soil needs can reduce excess nitrogen requirements and subsequent emissions.

b) Using precision agriculture techniques to apply fertilizer more accurately can reduce overapplication and subsequent emissions.

c) Incorporating nitrogen-fixing cover crops into crop rotations can reduce the need for nitrogen fertilizers and improve soil health.

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DOI: 10.19080/IJESNR.2023.32.556338

d) Implementing conservation tillage practices, such as no-till or reduced tillage, can reduce the amount of crop residue that decomposes and releases N_2O.

e) Using controlled-release fertilizers, which release nitrogen more slowly and reduce the potential for N_2O emissions.

Combining these and other management practices can help reduce and mitigate emissions from agricultural soils. Under the ERP-2030, the Government of Canada will incentivize producers to adopt the BMPs, including rotational grazing, cover cropping, regenerative agriculture, manure and fertilizer management, and agroforestry. The identified BMPs have the potential to reduce emissions and increase carbon sequestration in the soil and also offer several other benefits, such as improving soil health, increasing biodiversity, and enhancing the resilience and adaptation of agricultural landscapes. For instance, improving crop varieties and fertilization can lead to higher yields and lower input costs [77]. Therefore, selecting crop varieties better adapted to local growing conditions will have higher yields and less reliance on fertilizers and pesticides. Similarly, optimizing fertilizer application can improve nutrient use efficiency and reduce fertilizer costs while reducing the risk of nutrient runoff into waterways. Improving profitability in agriculture is important for the long-term sustainability of the sector, and adopting practices that reduce GHG emissions can be a win-win for farmers and the environment [78-82].

The ERP-2030 plans to provide financial assistance to help address some of the monetary barriers producers face in adopting these practices, making it easier for them to act. Nevertheless, there are challenges associated with each of the proposed techniques. The investments would only address economic barriers to adopting these practices leaving behind other difficulties. For example, farmers are perceived to apply optimum and precise amounts of fertilizers in their fields as per their needs using Precision Agriculture (PA) machines [83]. This will cut overutilization of fertilizers and GHG emissions thereof. However, the ground reality is that significant overapplication of fertilizers is practiced without considering intrafield variations in pursuit of bumper yields [84,85]. Despite their proven economic viability, farmers are less aligned to use PA technologies on technical and economic grounds [86]. The ERP might tackle the initial cost issue by providing subsidized machines. However, its wide-scale adoption has social and technical challenges that must be addressed [87-91]. Sophisticated training of farmers is required, as well as a change in classical mindset: "PA applications cannot give bumper yield, and therefore their profit margins will be significantly lowered." A comprehensive farmers' training program should be launched, where farmers are properly trained to use the machines and get convinced about their economic and environmental benefits. This is one of the ways how the effectiveness of the ERP can be increased in reducing GHGs from agricultural soils.

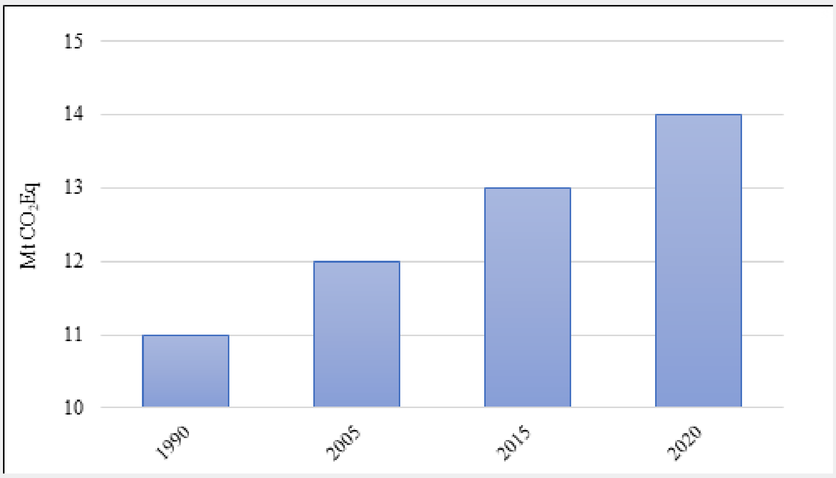

Figure 7: Temporal variations in on-farm fuel use emissions [15].

On-farm fuel use

It includes all the fuel used in the tillage, application of agrochemicals, and other food processing. Though it makes up less than 10% of the total on-farm GHG emissions but has the potential to be cut back significantly [92]. The GHG emissions by farm machinery fuel use highly vary depending on the type of commodity being produced, the scale of the farming operation, the geographic location of the farm, and the types of implements and machinery being used [93]. For example, a farm that produces crops using conventional tillage methods will typically use more fuel than a farm that uses no-till or reduced-till methods. Similarly, a farm with more powerful equipment will use more

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fuel than a minor operation that relies on manual labor or smaller machines. Regional constraints can also play a role in fuel-related GHG emissions, as farms in areas with higher energy costs or fewer renewable energy options may produce more emissions than those with access to cheaper or cleaner energy sources [94,95]. Ultimately, the variability of fuel-related GHG emissions in agriculture underscores the need for tailored, context-specific solutions to reduce emissions and increase sustainability in the sector [96]. The on-farm fuel use-associated emissions in Canada have been depicted in Figure 7.

A steady but lower increase in fuel use-related emissions is evident from the Figure 7. A variety of factors influence it. On-farm fuel use has been increasing, possibly due to agricultural expansion and intensification necessitating powerful equipment. Moreover, longer growing seasons and unpredictable weather conditions have been necessitating supplemental irrigation for sustainable production. Finally, more affordable prices make it easier for farmers to use larger equipment [4,97].

The Emission Reduction Plan-2030 targets a reduction of about 13Mt CO_2eq by reducing fertilizer use by 30% and adopting BMPs. The BMPs indirectly include reducing on-farm fuel used mainly for tilling, planting, harvesting, and transporting crops and livestock [18]. The government of Canada advises farmers to reduce on-farm fuel use by adopting conservation tillage practices, such as no-till or reduced tillage. It reduces the amount of fuel needed for tilling as well as decreases labor costs. In addition, it improves soil health by increasing organic matter and reducing soil erosion, resulting in higher crop yields and lower input costs [20].

Another approach is to use more fuel-efficient equipment, such as tractors and trucks, with better fuel economy ratings [98]. Transitioning to renewable energy sources, such as solar or wind power, can also help reduce on-farm fuel use [99]. Optimizing farming practices to reduce the need to transport inputs and outputs can significantly cut fuel use [100]. For example, precision agriculture tools can help farmers optimize fertilizers and other inputs, reducing the need to transport these products. Similarly, using local markets for inputs and outputs can reduce transportation needs and associated fuel use [101]. Farmers can reduce their GHG emissions and save on fuel costs by reducing on-farm fuel use, thus increasing profit margins.

There are technical and economic challenges to adopting these not envisaged under the ERP-2030. While no-till practices can be beneficial for reducing GHG emissions and improving soil health, they come with some limitations and challenges [102]. For example, no-till practices rely on crop residues such as mulch, which can compete with other uses, such as animal feed or bedding. In addition, no-till practices may not be as effective in poorly drained, clayey soils, especially in cold and wet conditions [103]. To address these challenges and enhance the applicability of no-till farming, region-specific research is needed to help identify the most suitable crops, cropping systems, and management practices for different soil types and climatic conditions [104]. Besides, it can strategize to alleviate biophysical, economic, social, and cultural constraints to adopting no-till practices. It is also important to note that sustainable production systems should aim to improve environmental quality while maintaining or increasing productivity. This will require the integration of no-till farming with other practices such as crop rotation, cover cropping, and agroforestry [105]. By adopting a range of sustainable practices, farmers can improve soil health, reduce GHG emissions, enhance the long-term sustainability of their operations, and thus help achieve the ERP-2030 targets and objectives.

Conclusion

Canada's agricultural sector contributes approximately 10% to the total GHG emissions, which includes significant contributions to the total CH_4 and N_2O emissions, with enteric fermentation, manure management, crop production, and on-farm fuel use being the main sources. Canada has set ambitious emissions reduction targets under the Paris Agreement-2015, with a goal to reduce total emissions by 30% below 2005 levels by 2030. Furthermore, the country's Emission Reduction Plan (ERP)-2030 targets a 40-45% reduction and aims to make the country net zero by 2050. The ERP-2030 includes a plan to reduce agricultural emissions by 19Mt CO_2eq yr^{-1} through measures such as increasing carbon sequestration from wetlands and grasslands, implementing beneficial management practices (BMPs), and reducing fertilizer use. The challenge in achieving the targeted reductions in agricultural emissions lies in the fact that these emissions have been stable over the past few decades while food and fiber requirements continue to grow. However, the agriculture sector is unique in reducing net emissions by decreasing emissions or increasing sequestration through BMPs, as rightly perceived in the plan. The ERP-2030 will provide subsidies to farmers (~$900 million) to adopt sustainable practices and use more energy-efficient equipment while supporting research and knowledge transfer. The subsidies provided under the ERP-2030 will help address some of the monetary barriers faced by producers in adopting these practices and technologies, leaving behind the associated social and technical challenges. To achieve its targets and objectives, it is highly important for Canada to follow the observe and improve strategy in the implementation of the ERP-2030. Continuous monitoring and evaluation of the effectiveness of the measures taken, along with feedback loops and adaptation to changing circumstances, will be necessary to achieve the desired outcomes.

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