Informing a strategy for reducing agricultural greenhouse gas emissions in Bristish Columbia

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Informing a strategy for reducing agricultural greenhouse gas emissions in BC

Report prepared for the Investment Agriculture Foundation

SUBMITTED TO

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SUBMITTED BY

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About Us

Navius Research Inc. is an independent and non-partisan consultancy based in Vancouver. We operate proprietary energy-economy modeling software designed to quantify the impacts of climate change mitigation policy on greenhouse gas emissions and the economy. We have been active in this field since 2008 and have become one of Canada's leading experts in modeling the impacts of energy and climate policy. Our analytical framework is used by clients across the country to inform energy and greenhouse gas abatement strategy.

We are proud to have worked with:

- Most provincial and territorial governments, as well as the federal government.
- Utilities, industry associations and energy companies.
- Non-profit and research organizations with an interest in energy, climate change and economics.

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Summary

The Investment Agriculture Foundation (IAF) commissioned Navius Research to evaluate greenhouse gas abatement opportunities in BC's agricultural sector. The objectives of this analysis are to identify the most promising technologies, fuels and actions that can help reduce emissions from agriculture and to quantify the level of abatement that is feasible in this sector in 2030 and beyond.

To accomplish these objectives, we employ Navius' gTech energy-economy model to simulate the achievement of BC's emissions targets and to understand the role of various abatement options in achieving those targets.

This study is an initial step to exploring the abatement potential in agriculture. It also resulted in a modeling framework that can be used to conduct deep analyses in the future, for example by examining the impact of specific policies on agricultural emissions and output.

Key findings of this analysis include:

- **Agricultural emissions are likely to grow in the absence of new policies**, resulting in an increasing gap between emissions and potential sectoral targets that are measured relative to a historical baseline. In 2019, the most recent year of available historical data, agriculture emissions were 17% above 2007 levels. By 2030, this could rise to as much as 30% unless the emissions intensity of agricultural operations declines.
- **Mitigation actions are available, or likely to be available in the future, for most sources of agricultural emissions**. The adoption of these actions could limit this increase to 16% above 2007 levels in 2030. For comparison, BC's provincial target calls for a 40% reduction in emissions across the economy.
- **Planting cover crops and implementing rotational grazing for cattle are relatively low-cost actions with high abatement potential**, making them a natural focus for near-term mitigation efforts. Other actions are more costly and/or have a lower abatement potential.
- **For BC to achieve its greenhouse gas targets in a cost-effective manner**:
    - All abatement measures in agronomy are widely adopted by 2030, including cover crops, 4R nitrogen management and nitrification inhibitors.

  - In livestock, anaerobic digestion is adopted wherever feasible, while other actions (manure composting, rotational grazing and feed additives for grain-fed cattle) are also widely implemented by 2030.

  - The transition to zero carbon energy sources and carriers (especially bioenergy and clean electricity) is underway by 2030 and complete by mid-century.

- **Greenhouse gas reductions can be achieved while maintaining agricultural output**, provided that policies are designed to incentivize emissions reductions while minimizing compliance costs.

- **Further research is needed to refine estimates regarding the feasibility, cost and abatement potential of greenhouse gas abatement options in agriculture.** While this study relied on the best available data sources available to the authors, uncertainty is in many cases high. This study provides a preliminary assessment of agriculture's potential contribution to meeting BC's greenhouse gas targets, which should be revised as new data emerge.

Contents

1. Introduction

BC has legislated targets for reducing greenhouse gas emissions 40% below 2007 levels by 2030, 60% by 2040 and 80% by 2050[1]. Against this background, the Investment Agriculture Foundation (IAF) is interested understanding options for reducing agricultural greenhouse gas emissions in BC, and in disseminating this information to industry and government.

Sources of emissions from agriculture include the combustion of fossil fuels, nitrous oxide from the application of organic and mineral nitrogen fertilizers, and methane generation from ruminants and other livestock. These sources are summarized in Canada's National Inventory Report, and in 2015 (the base year for this analysis) totalled 2,865 kt CO_2e, or approximately 5% of the provincial total[2].

Emissions from land use, land use change and forestry (LULUCF), such as emissions from turning grass land into crop land, can also partially be attributed to the agriculture sector. According to recent analysis, these sources amount to about 400 kt CO_2e in BC (in 2018)[3]. While this analysis does not attempt to forecast total LULUCF emissions, it does quantify the potential for abatement actions to reduce LULUCF emissions relative to what they otherwise would have been.

IAF commissioned Navius Research to evaluate greenhouse gas abatement opportunities in the agricultural sector. The objective of this analysis is to identify the most economically efficient technologies, fuels and actions that could help reduce emissions from agriculture and quantify the level of abatement that is likely to be feasible given commercially available and emerging mitigation options.

This report is structured as follows:

- Section 2 reviews the modeling approach and summarizes assumptions used to characterize BC's agriculture sector and relevant mitigation options.

[1] Climate Change Accountability Act. SBC 2007, c. 42. www.bclaws.gov.bc.ca/civix/document/id/complete/statreg/00_07042_01

[2] Environment and Climate Change Canada. 2021. National Inventory Report 1990-2019. Canada's Submission to the United Nations Framework Convention on Climate Change. https://unfccc.int/documents/271493

[3] Smukler, S., Borden, K., Norgaard, A., Li, C. 2021. Opportunity assessment of agricultural GHG reductions and carbon sinks. Project Summary and Recommendations. Report prepared for BC Ministry of Agriculture, Food and Fisheries.

- Section 3 summarizes findings from the analysis, focusing on answering the following questions:
  - Where are BC's agricultural emissions headed in the absence of new policies?
  - What are the most promising options to reduce agricultural emissions?
  - To what extent can known mitigation actions reduce agricultural emissions?
  - How can agriculture help achieve provincial emissions targets?
  - What is the economic impact of reducing agricultural emissions?

2. Approach

This section describes the methodology employed to explore the greenhouse gas reduction potential of agriculture in BC. Section 2.1 introduces gTech, the model used to conduct the analysis. It is followed by a description of how economic activity, energy use and emissions are allocated among agricultural sub-sectors (Section 2.2), an overview of modeled greenhouse gas mitigation options (Section 0) and a description of modeled scenarios (Section 2.2). Lastly, Section 2.5 identifies limitations associated with this analysis and opportunities for future research.

2.1. Our modeling toolkit

This project employs Navius' gTech energy-economy model to simulate the impact of greenhouse gas constraints on BC's agriculture sector. It is the most sophisticated model available for forecasting the economic effects of climate and energy policies in Canada, providing a comprehensive representation of most economic activity, energy use, and greenhouse gas emissions across North America.

gTech is well suited for informing a strategy to reduce agricultural emissions in BC because it:

- **Provides a detailed accounting of low carbon technologies and fuels that can lower greenhouse gas emissions in BC.** In total, gTech includes over 300 technologies (e.g., electric tractors, industrial heat pumps, biofuels, anaerobic digestion) across 70 end-uses (e.g., tractors, trucks, industrial process heat, manure management) that are available or are likely to become available in the coming decades. New research for this project expanded available abatement options to include those related to agronomy and livestock (please see Section 2).
- **Balances supply and demand for agricultural and other commodities across North America.** As a computable general equilibrium model, gTech simulates how markets (from labour to goods and services to policy compliance mechanisms) arrive at an equilibrium by adjusting prices. This means that if a policy imposes costs on BC's agricultural sector, the impact on competitiveness will be captured through demand for the affected commodities.
- **Simulates how firms and consumers make decisions in the real world, describing likely outcomes rather than simply prescribing financial cost-optimized solutions.** Technological choice is strongly influenced by behaviour in addition to financial

cost. For example, a farmer may be more willing to purchase an electric tractor after his or her neighbour purchases one.

- **Accounts for all substantive existing provincial and federal policies, including how they interact.** BC's GHG emissions are influenced by a large number of provincial and federal policies. Although climate policy efforts to date have not focused on agriculture, they may nevertheless impact agricultural emissions. For example, BC's renewable gas standard will encourage the development of anaerobic digestors.

For more information about gTech, please see Appendix A: gTech, starting on page 24.

2.2. Disaggregation of the agriculture sector

The representation of the agriculture sector in gTech was disaggregated into a variety of sub-sectors for this project. Table 1 outlines the sectors desired by IAF and the associated sectors that were modeled to best align with this categorization.

Table 1: Modeled agricultural sectors

IAF desired sector	Modeled sector	Component sector
Cattle and forage	Cattle and forage	Dairy
		Cattle
		Imputed feed
Field vegetables	Vegetables	Vegetables
Fruit, grapes and berries	Fruits and nuts	Fruits and nuts
Other	Grains (including wheat)	Grains
	Oilseeds (including canola)	Oilseeds
	Greenhouses	Greenhouse, nursery and floriculture products
	Other agriculture	Chickens
		Other animals
		Other agriculture
	Agriculture services	Agriculture services

Combustion emissions by sub-sector were disaggregated based on Environment and Climate Change Canada's National Inventory Report (NIR)[4] and the total value of production by sector in Statistics Canada's Supply-Use Tables[5]. The disaggregation of NIR reported emissions for enteric fermentation, manure management and agricultural soils is based on a variety of sources, including emissions coefficients reported in the NIR Part 2 and the Interpolated Census of Agriculture[6]. Further information is provided below.

While the method for disaggregating emissions into sub-sectors entails uncertainty due to limited data availability, total emissions for combustion, enteric fermentation, manure management and agricultural soils are aligned with the NIR.

2.2.1. Enteric fermentation

Enteric fermentation emissions are allocated among dairy, beef and other animals by using emissions factors from the NIR (in kg CH_4 per head of animal by type per year) multiplied by animal head counts as reported by Statistics Canada[7] (please see Table 2). The resulting split in CH_4 emissions between the dairy, beef, and other animals sectors is then used to disaggregate NIR emissions data by IPCC category into the three sub-categories. While calculated emissions achieve decent alignment with reported total emissions, they are used to create pro-rating factors which are applied to NIR emissions. This approach allows us to estimate sector disaggregation based on available information while ensuring that total emissions are perfectly aligned with historical.

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[4] Environment and Climate Change Canada. 2021. National Inventory Report 1990-2019. Canada's Submission to the United Nations Framework Convention on Climate Change. https://unfccc.int/documents/271493

[5] Statistics Canada. (2018). Supply and Use Tables. Available from: https://www150.statcan.gc.ca/n1/en/catalogue/15-602-X

[6] Agriculture and Agri-Food Canada. (2016). Interpolated Census of Agriculture. Available from: https://open.canada.ca/data/en/dataset/1dee8513-5c73-43b6-9446-25f7b985cd00.

[7] Statistics Canada. (2021). Number of cattle, by class and farm type. Available from: https://open.canada.ca/data/en/dataset/be38c86e-8364-40ee-a8eb-9ea11060bdce

Table 2: BC enteric fermentation greenhouse gas emissions by sector in kilotonnes CO2e in 2015

Dairy	Beef	Other animals
312	1,025	39

2.2.2. Manure management

Manure management emissions are allocated among dairy, beef, other animals and poultry (see Table 3). Methane emissions by animal category are calculated using emissions factors from the NIR (in kg CH_4 per head of animal by type per year) multiplied by head count data from Statistics Canada[8 9].

Direct N_2O emissions and N_2O emissions from manure nitrogen lost through volatilization and leaching during storage are calculated using emissions factors from the NIR (measured in grams of N_2O produced per head of animal by type per year) multiplied by head count data from Statistics Canada.

Methane and nitrogen dioxide emissions are then converted to kilotonnes CO_2e, summed within each animal category and used to create pro-rating factors, reflecting the split in emissions between these categories. These pro-rating factors are then applied to NIR emissions data by IPCC category to achieve perfect alignment with reported emissions.

Table 3: BC manure management greenhouse gas emissions by sector in kilotonnes CO_2e in 2015

Dairy	Beef	Poultry	Other animals
103	157	110	25

[8] Statistics Canada. (2021). Number of cattle, by class and farm type. Available from: https://open.canada.ca/data/en/dataset/be38c86e-8364-40ee-a8eb-9ea11060bdce

[9] Statistics Canada. (2017). Selected livestock and poultry, historical data. Available from: https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210015501

2.2.3. Agricultural soils

Table 4 shows agricultural soil greenhouse gas emissions disaggregated by sub-sector. The approach for disaggregation is described below.

Table 4: BC agricultural soil greenhouse gas emissions by sector in kilotonnes CO_2e in 2015.

Cattle	Other animals	Grains	Oilseeds	Greenhouse	Fruits and nuts	Vegetables	Other agriculture
176	8	106	25	162	17	6	13

Total manure (in kilograms of nitrogen produced by livestock) is calculated using emissions coefficients from the NIR (in kg of nitrogen produced by head of animal by type per year) multiplied with livestock data from Statistics Canada. The resulting calculated total of nitrogen produced by livestock in BC in 2015 is 55 kilotonnes.

Direct N_2O sources as well as indirect N_2O emissions through volatilization and leaching from manure left on pasture by animal type are calculated using calculated manure production as well as information about the percentage of manure left on pasture and an emissions factor (in grams of N_2O per kilogram nitrogen remaining on pasture per year), all from the NIR.

Manure available for application to agricultural soils as fertilizer is calculated using total manure production minus manure remaining on pasture and manure in solid storage (based on the NIR). The calculated total of manure nitrogen applied to agricultural soils is 13 kilotonnes. Emissions from manure in solid storage are assumed to be addressed under manure management. However, if all manure from solid storage is applied to agricultural soils, then the calculated total of manure nitrogen applied to soils would be 31 kilotonnes. It is important to note that this data is used to estimate the split between agricultural emissions, not total agricultural soils emissions. Changing this assumption would therefore not result in a change in total agricultural soils emissions but instead lead to small changes in emissions allocation between sub-sectors. The total amount of manure applied to agricultural soils as fertilizer is assigned to the various crop sectors according to the amount of land used by each sector (based on Statistics Canada[10]).

[10] Statistics Canada. (2017). Selected crops, historical data. Available from: https://open.canada.ca/data/en/dataset/256dbcbb-2d9c-4803-8d22-b7229db09d2f.

Manure nitrogen lost indirectly as N_2O through volatilization and leaching of manure applied to agricultural soils by sector is calculated using emissions factors from the NIR (in grams of N_2O per kilogram nitrogen applied to agricultural soils) multiplied by the amount of manure applied by each sector.

The total amount of chemical fertilizer applied to agricultural soils is calculated using data from Statistics Canada's supply use tables[11] which provide the use of ammonia and chemical fertilizers in greenhouses and crop production as a dollar value. Assuming that the average cost of nitrogen is $0.45 CAD per pound (at basic prices), 42 kilotonnes of chemical nitrogen was used in greenhouses and 42 kilotonnes of chemical nitrogen was used for other crop production in BC in 2015.

Fertilizer application by sector within crop production is further disaggregated based on the amount of land used for each crop type in BC (based on the Census of Agriculture).

N_2O emissions following the application of chemical fertilizer is calculated using emissions factors from the NIR (in grams of N_2O per kilogram of organic or inorganic fertilizer nitrogen applied to agricultural soils per year) multiplied by the amount of chemical nitrogen fertilizer applied to agricultural soils.

The resulting N_2O emissions by sector are then used to create pro-rating factors which are applied to NIR emissions data by IPCC category. Lastly, the resulting emissions by sector are then pro-rated again to align with NIR emissions data by IPCC category as well as by economic sector (reported as emissions for crop production, animal production, and on-farm fuel use).

[11] Statistics Canada. (2018). Supply and Use Tables. Available from: https://www150.statcan.gc.ca/n1/en/catalogue/15-602-X

2.3. Mitigation options

Table 5 lists the mitigation actions that are included in this analysis. Options to reduce emissions from energy as well as anaerobic digestion have been well characterized in gTech based on a variety of sources as noted. To characterize abatement practices for livestock and agronomy, this analysis relies on a recent report from the University of British Columbia[12].

The rest of this section summarizes assumptions for each of the mitigation actions.

Table 5: Overview of modeled greenhouse gas mitigation options

Abatement action	Combustion		Non-combustion			
	Stationary	Transport	Enteric fermentation	Manure management	Agricultural soils	LULUCF
Energy						
Battery electric vehicles		X				
Hydrogen	X	X				
Bioenergy	X	X				
Electric heat	X					
Agronomy						
4R nutrient management					X	
Cover crops					X	X
Nitrification inhibitor					X	
Plant woody perennials & preserve forests						X
Livestock						
Anaerobic digestion				X		
Cattle feed additive			X			
Manure composting				X		
Rotational grazing			X			X

[12] Norgaard, A., Li, C., Hamilton, H., Smukler, S., & Borden, K. 2021. Report 2: Multi-criteria framework for GHG emissions and co-benefits. Opportunity assessment of British Columbia's agricultural greenhouse gas reductions and carbon sinks. Report prepared for BC Ministry of Agriculture, Food and Fisheries.

2.3.1. Energy

Zero emission vehicles

Plug-in electric and hydrogen fuel cell vehicles are characterized based on the costs summarized in Table 6. These alternative-fuel drivetrains are available as an option for off-road farming vehicles (as well as for light-duty, medium-duty and heavy-duty road vehicles). The potential adoption of these technologies is a function of their upfront costs (for vehicles and charging infrastructure where appropriate), energy costs, and a dynamic representation of the barriers to their adoption (i.e., the implied cost of limited charging/fueling infrastructure, range concerns, unfamiliarity with the technologies, lack of supply). To account for uncertainty in future costs, we include sensitivities on the baseline cost assumptions that reflect the higher and lower range of expert forecasts.

Table 6: Zero emission vehicle costs

Technology/fuel	Cost	Sources
Plug-in electric vehicles	Battery pack costs decline from $492/kWh in 2015 to a minimum of $82/kWh.	Bloomberg New Energy Finance. (2020). Electric vehicle outlook; ICCT. (2019). Update on electric vehicle costs in the United States through 2030; Nykvist, B., F. Sprei, et al. (2019). "Assessing the progress toward lower priced long range battery electric vehicles." Energy Policy 124: 144-155.
Hydrogen fuel cell electric vehicles	Fuel cell stack system costs decline from $300/kW in 2015 to a minimum of $73/kW. Fuel tanks decline from $30/kWh in 2015 to a minimum of $11/kWh.	SA Consultants. (2016). Final report: Hydrogen storage system cost analysis; SA Consultants. (2017). Mass production cost estimation of direct H2 PEM fuel cell systems for transportation applications; IEA. (2020). Breakdown of cost-reduction potential for electrochemical devices by component category.

Bioenergy

Various forms of bioenergy can be introduced in the liquid or gaseous fuel streams as summarized in Table 7, which can reduce both stationary and transport combustion emissions from agriculture. Please note that the abatement costs shown are illustrative and change dynamically in the modeling as a function of various factors including fossil energy prices and renewable fuel feedstock costs. To account for the uncertainty in future costs, we include a sensitivity on future biofuel costs within the range of latest literature estimates.

Table 7: Summary of bioenergy abatement options

Technology/fuel	Approximate abatement cost ($/tonne CO_2e)	Sources
Second generation renewable natural gas	248	G4 Insights Inc. (2018). Our Technology; International Energy Agency Energy Technology System Analysis Programme (IEA ETSAP). (2013). Biogas and bio-syngas production; International Renewable Energy Association (IRENA). (2013). Road transport: the cost of renewable solutions; (S&T) Consultants Inc. (2012). Update of Advanced Biofuel Pathways in GHGenius.
Ethanol	156	
Cellulosic ethanol	172	
Biodiesel	116	
Hydrogenated renewable diesel	149	
Second generation renewable gasoline/diesel	411	

Notes: Abatement costs are illustrative and will vary in the modeling as they respond to changes in energy prices, technology learning and fuel carbon intensities, all of which are endogenously determined in gTech. Values are in 2020 CAD/t CO_2e captured, based on 15% discount rate and 30-year project life. Second generation renewable natural gas: feedstock at $70/dry tonne, approximate wholesale cost of $16/GJ. Ethanol: corn at $169/tonne, approximate wholesale cost of $23/GJ. Cellulosic ethanol: feedstock at $70/dry tonne, approximate wholesale cost of $31/GJ. Biodiesel: Canola seed at $414/tonne, approximate wholesale cost of $25/GJ. Hydrogenated renewable diesel: canola seed at $414/tonne, approximate wholesale cost of $26/GJ. Second generation renewable gasoline/diesel: feedstock at $70/dry tonne, approximate wholesale cost of $44/GJ.

2.3.2. Agronomy

4R nutrient management

Improving the accuracy of nitrogen fertilizer application can reduce N_2O emissions from agricultural soils. This mitigation action represents four best management practices, including applying (1) the right amount of fertilizer from (2) the right source at (3) the right time and to (4) the right place.

The abatement potential and cost of 4R nutrient management are summarized in Table 8, broken down for each modeled crop type.

Table 8: Characterization of 4R nutrient management

Crop type	Reduction factor (t CO_2e/ha/yr)	Total activity units in BC (hectare)	Upfront cost	Operating cost ($/ha/yr)	Max GHG reduction (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
Wheat	0.09	27,500	0	16.7	1.0 (0.7-1.2)	187 (149-249)
Canola	0.12	37,300	0	16.7	1.8 (1.3-2.2)	140 (112-187)
Grains (except wheat)	0.09	75,600	0	16.7	2.8 (2.1-3.6)	177 (142-237)
Fresh fruit and nuts	0.07	25,077	0	16.7	0.7 (0.6-0.9)	228 (183-305)
Vegetables	0.03	33,988	0	16.7	0.4 (0.3-0.5)	569 (455-759)
Total	**0.08**	**199,465**	**0**	**16.7**	**6.7 (5.1-8.4)**	**198 (158-264)**

Source: Norgaard et al. (2021).
Notes: (1) Assumes 60% of farms currently engage in these practices. (2) Uncertainty in max GHG reduction is based on uncertainty in reduction factor, assuming all remaining farms adopt this action. (3) Abatement estimate is valid for 2030 only.

Cover crops

Cover crops are planted to cover the soil rather than for the purpose of being harvested. They can reduce greenhouse gas emissions by increasing soil organic carbon and decreasing N_2O emissions.

The abatement potential and cost of planting cover crops are summarized in Table 9. This action reduces emissions from both agricultural soils and LULUCF.

Table 9: Characterization of planting cover crops

NIR category	Reduction factor (t CO_2e/ha/yr)	Total activity units in BC (hectare)	Upfront cost	Operating cost ($/ha/yr)	Max GHG reduction (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
Agricultural soils	0.67	196,688	0	48	112 (87-136)	72 (59-92)
LULUCF	0.96	196,688	0	48	161 (126-196)	50 (41-64)
Total	**1.63**	**196,688**	**0**	**48**	**273 (213-333)**	**29 (24-38)**

Source: Norgaard et al. (2021).

Notes: (1) Norgaard et al. (2021) suggest a maximum potential adoption rate of around 35%. (2) Costs do not include forgone revenue associated with reduced cash crops, which should be incorporated. (3) Abatement estimate is valid for 2030 only.

Nitrification inhibitor

Nitrification inhibitors can be added to fertilizers to supress the nitrification process in soil and reduce N_2O emissions. This abatement action is based on one specific type of nitrification inhibitor, dicyandiamide (DCD) for field crop production in BC.

The abatement potential and cost of nitrification inhibitors are summarized in Table 10, broken down for each modeled crop type.

Table 10: Characterization of nitrification inhibitor

Crop type	Reduction factor (t CO_2e/ha/yr)	Total activity units in BC (ha)	Upfront cost	Operating cost ($/ha/yr)	Max GHG reduction (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
Wheat	0.12	27,500	0	36	2.4 (2.1-2.6)	291 (260-331)
Canola	0.16	37,300	0	36	4.3 (3.8-4.8)	218 (195-248)
Grains (except wheat)	0.16	45,700	0	36	5.0 (4.4-5.6)	227 (203-258)
Vegetables	0.08	63,888	0	36	3.8 (3.3-4.2)	421 (376-478)
Fresh fruit and nuts	0.10	25,077	0	36	1.8 (1.6-2.0)	356 (318-404)
Total	**0.12**	**199,465**	**0**	**36**	**17.2 (15.2-19.3)**	**290 (259-329)**

Source: Norgaard et al. (2021).

Notes: (1) Assumes 30% of farms currently engage in this practice. (2) Costs assume $3.6/kg for DCD and a rate of 10kg/ha/yr. (3) We assume that the GHG reduction factor can be extended to 2050.

Plant woody perennials

Woody perennials such as trees and shrubs can mitigate greenhouse gas emissions by sequestering atmospheric CO_2. As trees and shrubs grow, their rate of sequestration increases until they reach maturity, after which the carbon remains stored until they die or are cut down. This mitigation action includes planting woody perennials as (1) vegetive buffers on cropland (i.e., along farm field edges) and (2) riparian buffers (i.e., waterways).

The abatement potential and cost of planting woody perennials are summarized in Table 11.

Table 11: Characterization of planting woody perennials

NIR category	Reduction factor (t CO_2e/ha/yr)	Total activity units in BC (ha)	Upfront cost	Operating cost ($/ha/yr)	Max GHG reduction in 2030 (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
LULUCF	16	54,809	3,480	0	218 (112-324)	57 (38-111)

Source: Norgaard et al. (2021).

Notes: (1) Upfront cost is that required to plant a hectare. (2) Costs do not include maintenance of buffers or forgone revenue from crops. (3) Abatement estimate is valid for 2030 only.

Preserve forests

Deforestation and conversion to cropland results in immediate greenhouse gas emissions from the loss of carbon stored in woody biomass and soil, as well as residual emissions from soil which last for many years. Preserving forest lands rather than converting them to cropland therefore results in avoided emissions.

The abatement potential and cost of preserving forests are summarized in Table 12.

Table 12: Characterization of preserving forests

Emissions source	Reduction factor (t CO_2e/ha/yr)	Total activity units in BC (ha)	Upfront cost	Operating cost ($/ha/yr)	Max GHG reduction in 2030 (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
LULUCF	98	1,980	2,364	0	194 (0-399)	5 (2-∞)

Source: Norgaard et al. (2021).

Notes: (1) Upfront cost is the value per hectare that farmers would require to preserve trees on their land for 20 years. (2) Large range in abatement cost reflects uncertainty in GHG reduction. (3) Abatement estimate is valid for 2030 only.

2.3.3. Livestock

Anaerobic digestion

Organic residues such as manure and crop residues can be used to create renewable natural gas through the process of anaerobic digestion. Anaerobic digestion captures manure emissions and therefore reduces livestock emissions. Captured methane is then turned into renewable natural gas (RNG) and can displace natural gas elsewhere in the economy. While the combustion of RNG leads to carbon emissions, it is produced from a waste product that would have otherwise been released into the atmosphere as methane. Methane has about 30 times higher global warming potential than carbon dioxide over a 100-year time period.

The assumed cost of producing renewable natural gas via anaerobic digestion is shown in Table 13.

Table 13: Characterization of anaerobic digestion

Technology	Archetype production (TJ/yr)	Upfront cost (million 2019$)	Operating cost (2019$/GJ)	Cost of RNG output (2019$/GJ)
Anerobic digestion	23	1.7	1.9	12.7

Source: International Energy Agency (IEA) Energy Technology System Analysis Program (ETSAP) (2013). Biogas and Bio-syngas Production. https://iea-etsap.org/E-TechDS/PDF/P11_BiogasProd_ML_Dec2013_GSOK.pdf.
Notes: (1) Production of RNG is constrained to agricultural output. (2) Excludes value of digestate. (3) Norgaard et al. (2021) assume that 62.5% (+/-20%) of agricultural residues could be used to create renewable natura gas, based on a recent study finding that 50-75% of feedstocks in BC were considered as “easily accessible”.

Manure composting

Composting is an alternative manure storage method to reduce greenhouse gas emissions. Specifically, aerobic composting reduces the amount of CH_4 produced by anaerobic decomposition of organic matter.

The abatement potential and cost of manure composting is summarized in Table 14.

Table 14: Characterization of manure composting

Livestock type	Reduction factor (t CO_2e/1000 hd/yr)	Total activity units in BC (1000 heads of livestock)	Upfront cost	Operating cost	Max GHG reduction (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
Dairy cattle	751	84	21,429	0	40 (21-58)	6 (4-11)
Beef cattle	361	26	21,429	0	6 (3-9)	12 (8-23)
Total	**659**	**110**	**21,429**	**0**	**45 (24-67)**	**7 (5-13)**

Source: Norgaard et al. (2021).

Notes: (1) Upfront cost is that of building a composting facility suitable for 1000 heads of cattle, with a volume of 25 cubic yards and a lifespan of 15-25 years. (2) No operating costs specified. (3) We assume that the GHG reduction factor can be extended to 2050.

Feed additives

Feed additives can reduce methane associated with enteric fermentation. This abatement action is based on the additive 3-nitrooxypropanol (3NOP), a synthetic compound which inhibits methanogenic bacteria from performing the final step of methane production in livestock's rumen.

The abatement potential and cost of feed additives are summarized in Table 15.

Table 15: Characterization of feed additives

Livestock type	Reduction factor (t CO_2e/1000 hd/yr)	Total activity units in BC (1000 heads of livestock)	Upfront cost	Operating cost ($/head/yr)	Max GHG reduction in 2030 (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
Dairy cattle	925	84	0	25 (10-50)	77 (59-95)	27 (9-70)
Beef cattle	1,522	26	0	25 (10-50)	40 (27-52)	16 (5-48)
Total	**1,066**	**110**	0	**25 (10-50)**	**117 (95-138)**	**12 (8-58)**

Source: Norgaard et al. (2021).

Notes: (1) Costs are preliminary because 3NOP feed additive is not yet approved for use in Canada. (2) Abatement cost range reflects uncertainty in cost and GHG reduction potential. (3) We assume that the GHG reduction factor can be extended to 2050.

Rotational grazing

Rotational grazing is the practice of circulating livestock through multiple, separate paddocks. Compared to continuous grazing in a single paddock, rotational grazing can increase vegetation growth and soil organic carbon.

The abatement potential and cost of rotational grazing are summarized in Table 16. It results emissions associated with enteric fermentation as well as LULUCF.

Table 16: Characterization of rotational grazing

Emissions source	Reduction factor (t CO_2e/ha/yr)	Total activity units in BC (ha)	Upfront cost	Operating cost ($/ha/yr)	Max GHG reduction in 2030 (kt CO_2e/yr)	Abatement cost ($/t CO_2e)
Enteric fermentation	0.6	1,639,074	0	24	161 (103-219)	39 (28-60)
LULUCF	0.5	1,639,074	0	24	131 (84-178)	47 (35-74)
Total	**1.1**	**1,639,074**	**0**	**24**	**292 (186-397)**	**21 (16-33)**

Source: Norgaard et al. (2021).

Notes: (1) Based on “intensive" rotational grazing as described by Norgaard et al. (2021). “Basic” option not shown because it was more expensive on a $/t basis. (2) Abatement estimate is valid for 2030 only.

2.4. Scenarios

Scenarios modeled for this analysis vary according to two dimensions, as shown in Table 17.

First, different GHG reduction requirements were simulated, including:

- **Current policy.** This forecast describes how the agriculture sector develops under a business-as-usual scenario that includes implemented federal and provincial policies. It serves as a benchmark against which greenhouse gas abatement efforts can be measured. Although climate policy efforts to date have not focused on agriculture, they may nevertheless impact agricultural emissions. For example, BC’s renewable gas standard will encourage the adoption of anaerobic digestion. Likewise, BC’s various policies to boost the adoption of zero emission vehicles for on-road applications could spill over to off-road applications like tractors.
- **Target scenario.** This forecast describes a scenario in which BC achieves its greenhouse gas reduction targets of 40% below 2007 levels by 2030, 60% by 2040 and 80% by 2050. It identifies the most economically efficient technologies, fuels and actions required to achieve these targets, beyond those required by current policy.

Second, due to the large amount of uncertainty in the abatement potential and cost of alternative mitigation actions, a sensitivity analysis was conducted to explore the impact of low and high-cost assumptions.

Table 17: Scenario overview

		Sensitivity on abatement costs		
		Reference	Low	High
GHG reduction requirement	Current policy			
	Province achieves 80% reduction by 2050			

Notes: Abatement costs sensitivity – cost and potential

2.5. Limitations

Despite using the best available forecasting methods and assumptions possible within the scope of this project, the development of the economy, including BC's agricultural sector, is uncertain.

In particular, we note the following sources of uncertainty:

- **The rate of technological change.** Emerging technologies and practices, from electric batteries to feed additives to reduce enteric fermentation, are rapidly evolving. The ultimate performance and cost of emerging technologies could vary from that assumed in this analysis. Further research is needed to refine many of the estimates for the feasibility, cost and abatement potential of greenhouse gas abatement options in agriculture.
- **Biophysical flows.** Non-energy related greenhouse gas emissions from agriculture depend on a complex interplay between human activity and the environment. We have relied on recent research for BC that quantifies the potential abatement from agronomy and livestock greenhouse gas reduction measures, but our understanding is that this research is at a relatively early stage relative to evaluation of energy-related abatement options.
- **The disaggregation of 2015 agricultural emissions into sub-categories.** Limited data availability results in uncertainty regarding the disaggregation of agriculture emissions into more detailed sub-sectors. While the emission distribution between sub-sectors is uncertain, total emissions from combustion, enteric fermentation, methane management, and agricultural soils are aligned with emissions data

reported by the National Inventory Report. Future work could refine the approach for emissions sub-sector disaggregation.

- **The timing of greenhouse gas reductions.** The complex nature of biophysical flows means that greenhouse gas reductions from agronomy and livestock actions are not constant over time. We have relied on estimates for 2030 and extrapolated to 2050 where possible.
- **Co-benefits and costs.** The adoption of many abatement options in agriculture result in both co-benefits (e.g., enhanced biodiversity and long-term productivity) and costs (e.g., conflict with other priorities such as efficiency). In the future, the adoption of the mitigation actions described above could be considered in this broader context.

3. Findings

This section presents findings from the analysis. It is structured to answer the following questions:

- Where are BC's agricultural emissions headed in the absence of new policies?
- What are the most promising options to reduce agricultural emissions in BC?
- To what extent can known mitigation actions reduce agricultural emissions?
- How can agriculture help achieve provincial emissions targets?
- What is the economic impact of reducing agricultural emissions?

3.1.1. Where are BC's agricultural emissions headed in the absence of new policies?

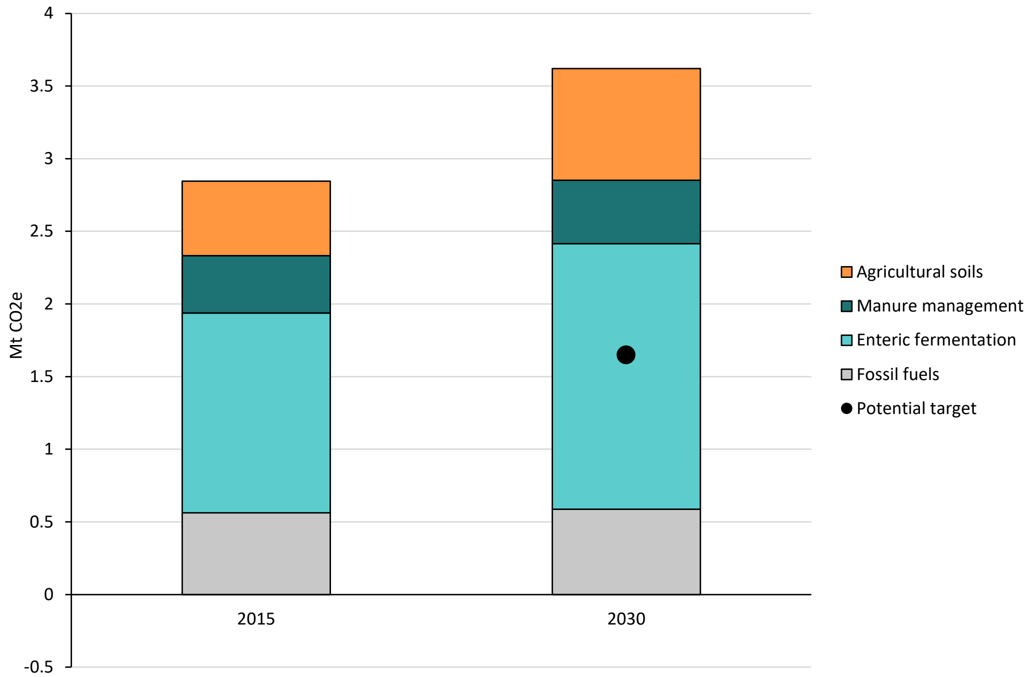
Agricultural output is likely to continue to expand in BC due to demographic and economic growth, and would result in growing emissions without the adoption of greenhouse gas mitigation measures.

In the absence of new policies, emissions from agricultural sources (soils, enteric fermentation, manure management and fossil fuels) could rise from 2.8 Mt in 2015 to 3.6 Mt by 2030 (see Figure 1), unless the emissions intensity of agricultural operations improves.

It is important to note that total agricultural emissions reported here do not include emissions from land use, land-use change, and forestry (LULUCF), such as emissions from deforestation for crop land development. LULUCF emissions are not reported in the National Inventory Report and were outside the scope of this project.

The emissions trend in Figure 1 suggests that new policies will be needed to close the gap between projected emissions and any potential sectoral targets that are implemented in BC.

Figure 1: Agricultural greenhouse gas emissions forecast, current policies



Source: Navius forecast using gTech. Excludes LULUCF. Please note that this figure shows an economy-wide provincial emissions target of a 40% reduction from 2007 levels by 2030, applied to the agricultural sector (i.e., reducing agricultural emissions by 40%). BC also has targets of 60% by 2040 and 80% by 2050.

3.1.2. What are the most promising options to reduce agricultural emissions in BC?

As described in Section 3, mitigation actions are available (or likely to be available in the future) for most sources of agricultural emissions.

Several low-cost actions have high abatement potential, including planting cover crops and rotational grazing. Other options are higher cost and/or have lower abatement potential. All abatement actions are summarized in Table 18. Important things to note are:

- Relatively low-cost abatement options (less than about $50/t) include planting cover crops, rotational grazing, cattle feed additives and manure composting.
- Medium-cost abatement options (between about $50/t and $150/t) include planting woody perennials and preserving forests, adopting plug-in electric tractors and switching to electric heat.

- Higher-cost abatement options (above about $150/t) include 4R nutrient management, nitrification inhibitors, anaerobic digestors and fuel switching to hydrogen or biofuels.

Please note that this assessment of costs focusses exclusively on emissions reductions, leaving for future analysis to consider the significance of co-benefits such as biodiversity and long-term productivity).

Table 18: Overview of abatement options

Abatement action	Abatement cost in 2030[1]	Abatement potential in 2030[2]
Agronomy		
4R nutrient management	High	Low
Cover crops	Low	High
Nitrification inhibitor – DCD	High	Low
Plant woody perennials & preserve forests	Medium	High
Livestock		
Manure composting	Low	Low
Anaerobic digestion	High	High
Cattle feed additive	Low	Medium
Rotational grazing	Low	High
Energy		
Plug-in electric vehicles	Medium	High
Hydrogen fuel cell vehicles	High	High
Bioenergy	High	High
Electric heat	Medium	High

Table is illustrative. Detailed assumptions and sources are provided in Section 3. Notes: (1) Abatement cost categories: low =< $50/t CO_2e, medium = $51-150/t and high => $150/t. (2) Abatement potential categories: low =< 100 kt CO_2e, medium = 101-200 kt and high => 200 kt. Cost estimates do not account for co-benefits, such as reduced needed for nitrogen fertilizers, and may not account for all costs.

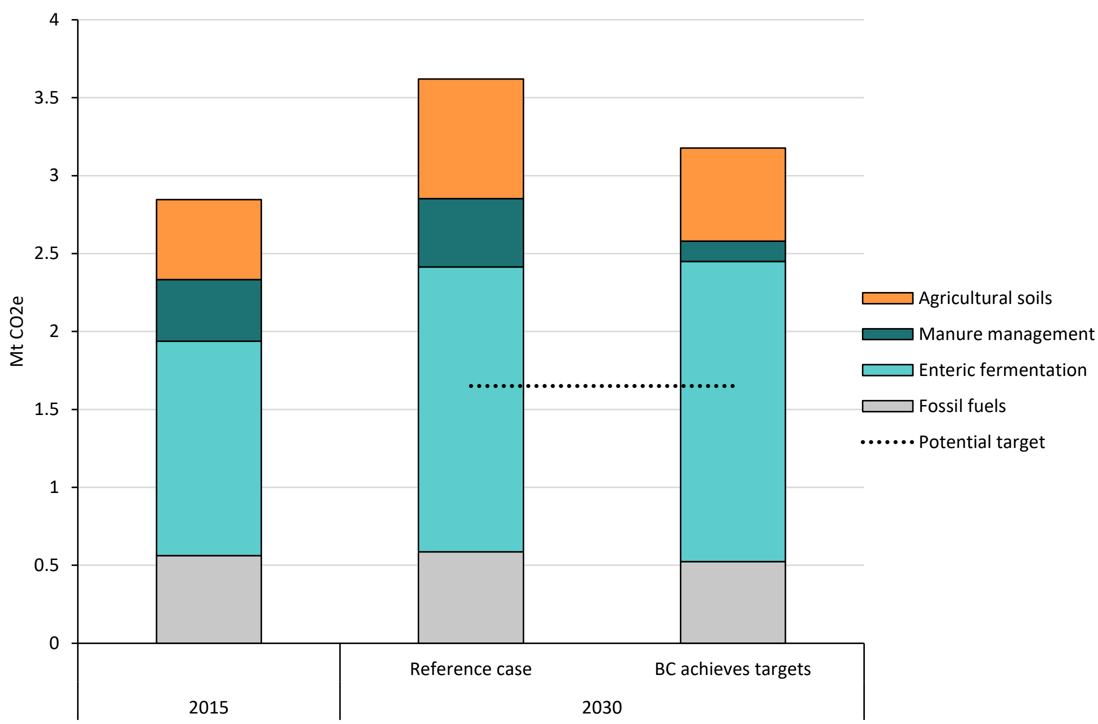
3.1.3. To what extent can known mitigation actions reduce agricultural emissions?

Using known mitigation actions, BC's agriculture sector could reduce emissions by 0.4 Mt in 2030, relative to what they would be in the absence of new policies (see Figure 2). Put another way, greater adoption of mitigation actions presented in Section 3.1.2 could limit the increase in agricultural emissions to 16% above 2007 levels in 2030.

Reducing emissions beyond this level would require 1) mitigation actions beyond those identified in this analysis and/or 2) offsets via negative emissions technologies, such as direct air capture.

Based on the simulated adoption rate of rotational grazing and use of cover crops and assuming that planting woody perennials and forest preservation are pursued to the biophysical limit, emission reductions from land-use, land-use change and forestry (LULUCF) can be estimated. The LULUCF reduction potential from those actions is estimated to be between 0.2 and 1.1 Mt CO_2e.

Figure 2: Agricultural greenhouse gas emissions forecast



Source: Navius forecast using gTech. Excludes LULUCF.

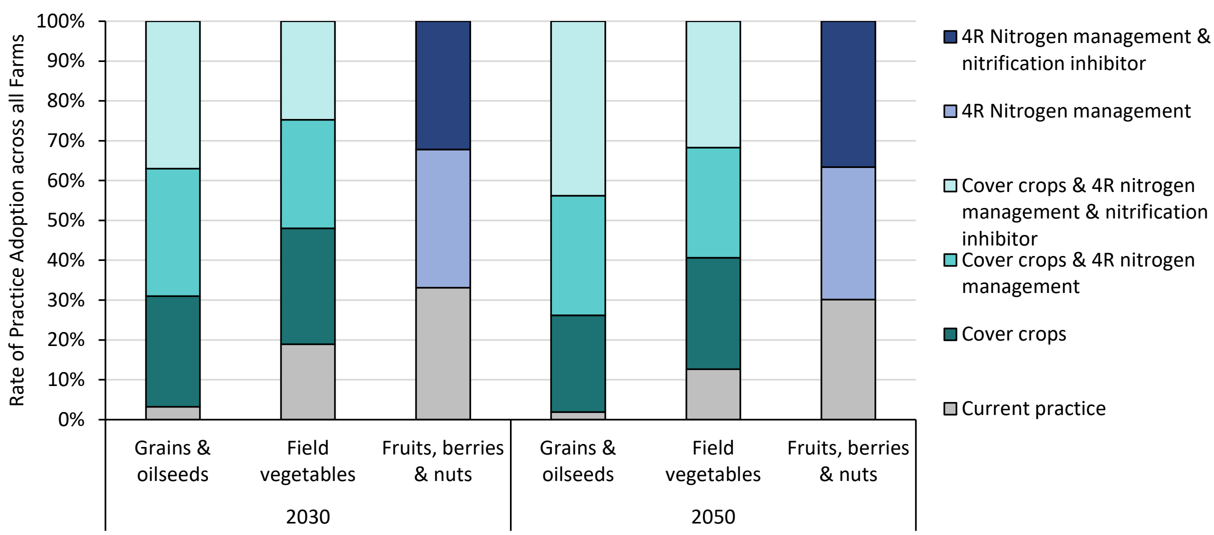
3.1.4. How can agriculture help achieve provincial emissions targets?

The stringency of BC's greenhouse gas reduction targets necessitates a high level of abatement effort. More specifically, the cost of achieving these targets is higher than the cost of most abatement options for agriculture identified in this analysis (i.e., several hundred dollars per tonne carbon dioxide equivalent).

This suggests that under a scenario in which BC achieves its greenhouse gas targets in the most cost-effective manner:

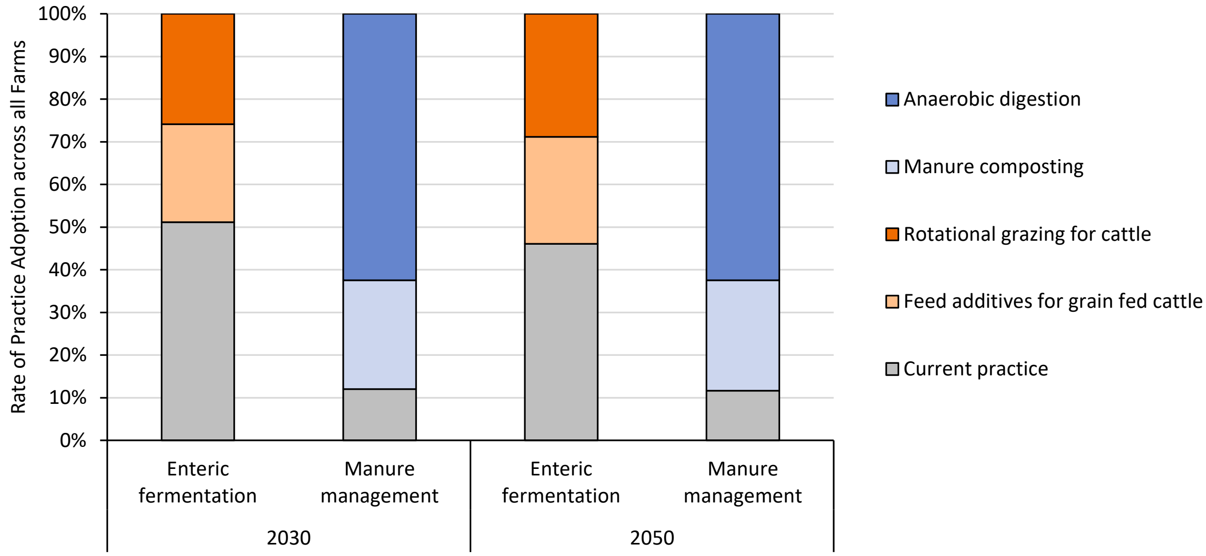
- All abatement measures in agronomy are widely adopted by 2030 (including cover crops, 4R nitrogen management and nitrification inhibitors), as shown in Figure 3.
- In livestock, anaerobic digestion is adopted wherever feasible, while other actions (anaerobic digestion, manure composting, rotational grazing and feed additives for grain-fed cattle) are also widely implemented by 2030, as shown in Figure 4.
- The transition to zero carbon energy sources and carriers (clean electricity, bioenergy and hydrogen) is underway by 2030 and complete by mid-century, as shown in Figure 5.

Figure 3: Adoption of abatement measures in agronomy, provincial target scenario



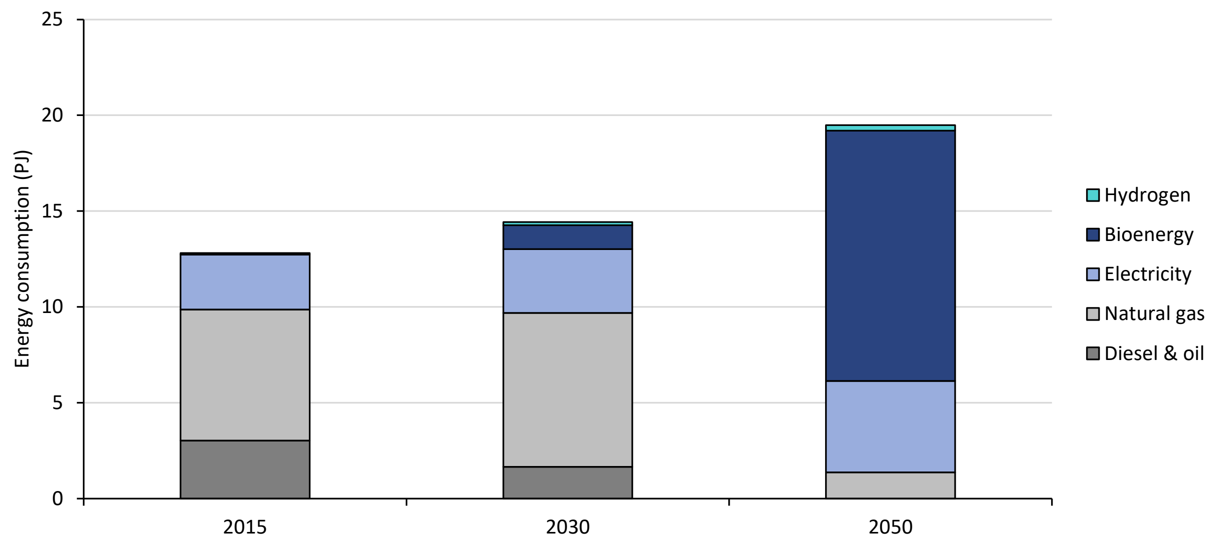
Source: Navius forecast using gTech.

Figure 4: Adoption of abatement measures in livestock, provincial target scenario



Source: Navius forecast using gTech.

Figure 5: Agricultural energy consumption by fuel, provincial target scenario



Source: Navius forecast using gTech.

3.1.5. What is the economic impact of reducing agricultural emissions?

Greenhouse gas reductions can be achieved while sustaining economic growth in agriculture. Agricultural output and jobs continue to grow in BC under all scenarios examined, including those in which BC achieves its provincial greenhouse gas targets (see Figure 6).

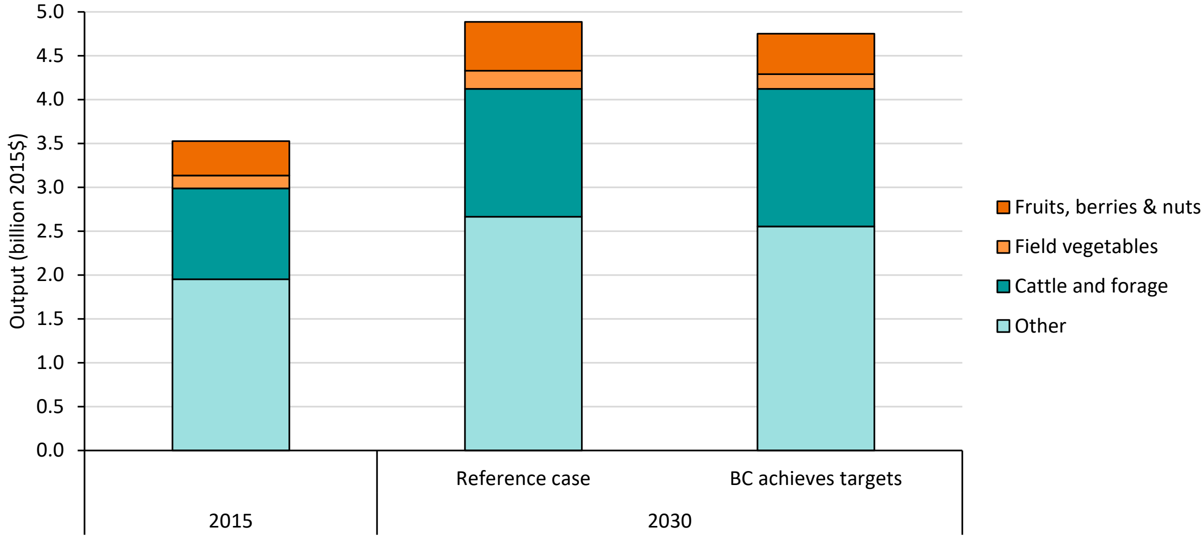
Smart policy design can ensure BC's agriculture sector remains competitive while reducing greenhouse gas emissions. Policy design determines compliances costs borne by industry, and hence economic impacts. For example, regulations may impose costs that are exclusively borne by regulated entities. Conversely, other policies may provide an incentive to reduce emissions while reducing overall compliance costs (e.g., through output rebates or subsidies).

For example, anaerobic digestion is a relatively high-cost abatement action relative to other abatement options. Nevertheless, the province's renewable natural gas mandate is likely to encourage the adoption of this technology to the benefit of the agriculture sector (i.e., because natural gas utilities can comply with the policy by paying farmers for renewable gas).

Providing policy recommendations is beyond the scope of this analysis. Nevertheless, decision makers may wish to consider the following guiding principles when it comes to developing policies to reduce agricultural emissions in BC:

- In the short-term, target abatement actions that have a relatively high abatement potential and low cost such as planting cover crops and rotational grazing for cattle.
- Given that achieving BC's targets is likely to require the adoption of costlier abatement actions, ensure that policies are designed to protect sector competitiveness.

Figure 6: Agricultural output



Source: Navius forecast using gTech.

4. Key insights

Key insights of this analysis include:

- **Agricultural emissions are likely to grow in the absence of new policies**, resulting in an increasing gap between emissions and potential sectoral targets that are measured relative to a historical baseline. In 2019, the most recent year of available historical data, agriculture emissions were 17% above 2007 levels. By 2030, this could rise to as much as 30% unless the emissions intensity of agricultural operations declines.

- **Mitigation actions are available, or likely to be available in the future, for most sources of agricultural emissions**. The adoption of these actions could limit this increase to 16% above 2007 levels in 2030. For comparison, BC's provincial target calls for a 40% reduction in emissions across the economy.

- **Planting cover crops and implementing rotational grazing for cattle are relatively low-cost actions with high abatement potential**, making them a natural focus for near-term mitigation efforts. Other actions are more costly and/or have a lower abatement potential.

- **For BC to achieve its greenhouse gas targets in a cost-effective manner**:

  - All abatement measures in agronomy are widely adopted by 2030, including cover crops, 4R nitrogen management and nitrification inhibitors.

  - In livestock, anaerobic digestion is adopted wherever feasible, while other actions (manure composting, rotational grazing and feed additives for grain-fed cattle) are also widely implemented by 2030.

  - The transition to zero carbon energy sources and carriers (especially bioenergy and clean electricity) is underway by 2030 and complete by mid-century.

- **Greenhouse gas reductions can be achieved while maintaining agricultural output**, provided that policies are designed to incentivize emissions reductions while minimizing compliance costs.

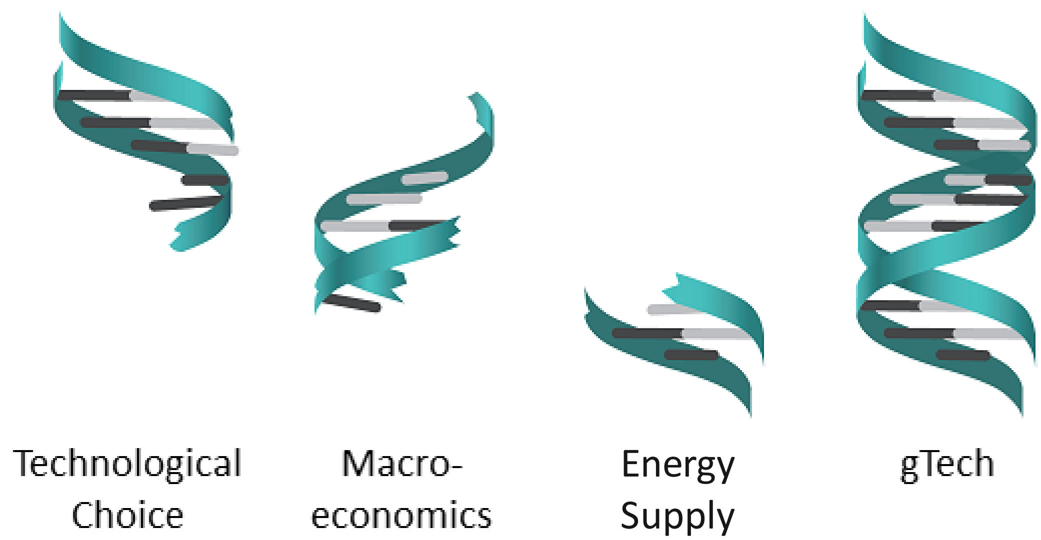
- **Further research is needed to refine estimates regarding the feasibility, cost and abatement potential of greenhouse gas abatement options in agriculture.** While this study relied on the best available data sources available to the authors, uncertainty is in many cases high. This study provides a preliminary assessment of agriculture's potential contribution to meeting BC's greenhouse gas targets, which should be revised as new data emerge.

Appendix A: gTech

gTech is unique among energy-economy models because it combines features that are typically only found in separate models (see Figure 7):

- A realistic representation of how households and firms select technologies and processes that affect their energy consumption and greenhouse gas emissions.
- An exhaustive accounting of the economy at large, including how provinces and territories interact with each other and the rest of the world.
- A detailed representation of energy supply, including liquid fuel (crude oil and biofuel), gaseous fuel (natural gas and renewable natural gas) and electricity.

Figure 7: The gTech model



gTech builds on three of Navius' previous models (CIMS, GEEM and OILTRANS/IESD), combining their best elements into a comprehensive integrated framework.

Simulating technological choice

Unlike most computable general equilibrium (CGE) models, gTech contains substantial technological detail, such that it can account for the complexities of the energy economy system. Technological detail allows gTech to examine the impact of technology deployment on energy consumption, GHG emissions and the broader economy. gTech is designed to provide a forecast of how households and firms adopt technologies, and how technological adoption affects energy and emissions profiles. It simulates how energy prices, technology costs and policies affect which technologies are used to provide energy end-uses (e.g., lighting, process heating, mobility etc.). These choices in turn affect energy consumption, air emissions, capital costs, operating costs and energy costs. The model also accounts for the intangible and interactive technological, behavioural, and economic factors that accompany energy use and GHG emission policies.

Understanding the macroeconomic impacts of policy

As a CGE model, gTech represents key economic transactions within the economy allowing it to forecast the economic impacts of climate policies. These economic transactions include:

- **Interlinkages between sectors of the economy.** gTech explicitly represents 120 sectors of the economy (e.g., construction, cement manufacturing, petroleum refining). Each sector of the economy is characterized by the goods it produces (e.g., cement), and the inputs required to production (labor, capital, energy, etc.). As an equilibrium mode, gTech simulates how every sector of the economy returns to equilibrium if a policy is introduced or if economic conditions change. For example, if a policy reduces construction activity, demand for construction inputs, such as cement, would also be reduced.
- **Interlinkages between households and sectors of the economy.** Households lend their time and savings to industry in exchange for income. Any change in income generation within a province affects household income.
- **Interlinkages between regions.** gTech represents a total of 12 regions in North America, including each Canadian province, a single region representing the territories, and the United States. gTech accounts for bilateral trade between these regions as well as international trade beyond North America. Policies implemented in a given region can then affect the level of trade that occurs with the rest of the world.

Understanding energy supply markets

gTech accounts for all major energy supply markets, including electricity, refined petroleum products, natural gas and hydrogen. Each market is characterized by resource availability and production costs by province and territory, as well as costs and constraints (e.g., pipeline capacity) of transporting energy between regions.

Low-carbon energy sources can be introduced within each fuel stream in response to policy, such as renewable electricity and bioenergy. The model accounts for the availability and cost of bioenergy feedstocks, allowing it to provide insight about the economic effects of emission reduction policy, biofuels policy and the approval of pipelines.

gTech: The benefits of merging macroeconomics with technological detail

By merging the three features described above (technological detail, macroeconomic dynamics, and energy supply dynamics), gTech can provide extensive insight into the effect of climate and energy policy.

First, gTech can provide insights related to technological change by answering questions such as:

- How do policies affect technological adoption (e.g., how many electric vehicles are likely to be on the road in 2030 or 2050)?
- How does technological adoption affect energy consumption and greenhouse gas emissions?

Second, gTech can provide insights related to macroeconomics by answering questions such as:

- How do policies affect gross domestic product?
- How do policies affect individual sectors of the economy?
- Are households affected by the policy?
- Does the policy affect energy prices or any other price in the model (e.g., food prices)?

Third, gTech answers questions related to its energy supply modules:

- Will a policy generate more supply of renewable fuels or greater demand for electricity?
- Does policy affect the cost of transporting refined petroleum products, and therefore the price of gasoline in Canada?

Finally, gTech provides insight into areas where there is overlap between its various features:

- What is the effect of investing carbon revenue into low- and zero-carbon technologies? This question can only be answered with a model such as gTech.

- What are the macroeconomic impacts of technology-focused policies (e.g., how might a zero-emissions vehicle standard impact GDP)?
- Do biofuels focused policies affect (1) technological choice and (2) the macroeconomy?

This modeling toolkit allows for a comprehensive examination of the impacts of energy and climate change policy in Canada.

At Navius, we offer our clients the confidence to make informed decisions related to energy, the economy, and the environment.

We take a collaborative approach to projects, drawing on a unique suite of modeling, research and communication tools to provide impartial analysis and clear advice.

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