THE UNIVERSITY OF BRITISH COLUMBIA

Opportunity Assessment of British Columbia's Agricultural Greenhouse Gas Reductions and Carbon Sinks

Report 2: Multi-criteria Framework for GHG Emissions and Co-benefits

Opportunity Assessment of British Columbia's Agricultural Greenhouse Gas Reductions and Carbon Sinks

June 2021

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BC Ministry of Agriculture, Food and Fisheries

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UBC Sustainable Agricultural Landscapes Lab

The Sustainable Agricultural Landscapes Lab contributes to understanding the ecology of and management for an agricultural system that meets current needs without compromising the needs of future generations. A major focus is to evaluate the multiple environmental impacts and ecological interactions for various management options, and to provide a better understanding across a diversity of agroecosystems and social and economic contexts.

Funding

This projected was funded in part by the governments of Canada and British Columbia through the Canadian Agricultural Partnership, a federal-provincial-territorial initiative.

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Citation

In-text: Norgaard et al. 2021

Reference list: 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.

Acknowledgements

This project was led by Anna Stemberger, Climate Change Specialist with the BC Ministry of Agriculture, Food and Fisheries. Considerable support was provided by members of the project delivery team, including Dieter Geesing, Lisa Zabek, and Julie Galloway from BC Ministry of Agriculture, Food, and Fisheries, and Alvaro Diaz from the Climate Action Secretariat of BC Ministry of Environment and Climate Change Strategy. Appreciations are also extended to Doug MacDonald and Corey Flemming of Environment and Climate Change Canada, and Dr. Brian McConkey and Arzeena Hamir of Farmers for Climate Solutions, for generously sharing their time and technical materials to advance this analysis.

Cover photograph

Incorporating compost into research plots on a vegetable farm in Pemberton, B.C.
Photo credit: Amy Norgaard, UBC Sustainable Agricultural Landscapes Lab.

Executive Summary

This is the second of three reports prepared by the Sustainable Agricultural Landscapes laboratory at the University of British Columbia as part of the project *Opportunity Assessment of Agricultural GHG Reductions and Carbon Sinks*. The overarching objective of this report is to summarize progress towards the development of a multi-criteria framework (MCF) that can be used to collectively assess greenhouse gas (GHG) benefits (emission reductions and sinks), environmental co-benefits, and adoptability considerations of agricultural beneficial management practices (BMPs). This work is intended to support the development of BMPs that can help meet GHG reduction targets. The specific objectives of this report are to:

- Assess options, establish protocols, and facilitate an iterative design for an MCF with long-term utility
- Review potential BMPs and catalogue their GHG benefits and co-benefits
- Identify a preliminary set of BMPs to demonstrate the utility of the MCF
- Develop a set of methods for quantifying BMP GHG benefits and build a simple database that can be integrated easily into the MCF
- Demonstrate the MCFs capabilities to evaluate this preliminary set of BMPs and estimate their potential contribution to GHG emission reduction targets

Developing climate change mitigation strategies for the agriculture sector in British Columbia (BC) requires an accurate understanding of how BMPs can contribute to GHG benefits that account for both emission reductions and carbon sinks. In prioritizing BMPs it is also important to consider their associated costs and potential co-benefits as these can be critical in determining adoption rates and overall outcomes. This report summarizes preliminary work on the development and implementation of a multi-criteria framework (MCF) to be used by the BC Ministry of Agriculture, Food and Fisheries (AFF) to compare BMP options for agricultural activities in relation to 11 criteria identified as important in meeting BMP programming objectives.

We developed and implemented an MCF based in Microsoft Excel (MCF Excel tool: *BMP MCF tool.xlsx*) that can systematically evaluate, compare and rank the performance of BMPs based on the following 11 criteria and associated uncertainties:

GHG benefit criteria:

1. short-term GHG benefit potential (to meet reduction targets by 2030)

2. long-term GHG benefit potential (beyond the year 2030)
3. feasibility of monitoring, reporting, and verification (MRV)

Environmental co-benefit criteria:

4. soil quality
5. water quality
6. air quality
7. biodiversity / pest management

Adoptability criteria:

8. cost of adoption
9. economic risks/benefits
10. adaptation to climate change
11. regulatory barriers

The MCF Excel tool is integrated with a pilot BMP database to automatically conduct performance calculations on BMPs that a user selects from a drop-down menu. BMPs can be analyzed by relevant commodity type (e.g. potato production, or dairy cattle), emissions category (i.e. Agriculture, Energy or Land Use, Land Use Change and Forestry (LULUCF)), greenhouse gas (i.e. carbon dioxide, methane, or nitrous oxide). To initiate the use of the MCF Excel tool, we compiled and populated the pilot BMP database with data on a preliminary list of BMPs that are of high interest based on their potential to mitigate GHG emissions from the largest emitting subcategories from the Agriculture, Energy and LULUCF sectors, relevancy across a cross-section of BC agriculture, and documented viability for GHG benefits provincially and/or nationally:

Agriculture – reduced CH_4 and N_2O emissions

- 4R nutrient management
- Cattle feed additive: 3-nitrooxypropanol (3NOP)
- Manure composting
- Nitrification inhibitor: dicyandiamide (DCD)

Energy – reduced CO_2 emissions

- Anaerobic digestion
- Best-in-class greenhouse retrofits
- Replace diesel tractors with electric

LULUCF – reduced CO_2 emissions and increased carbon sequestration

- Plant woody perennials – riparian and vegetative buffers on crown and private pasture and ARL land
- Preserve forest from conversion to cropland

Combined (Agriculture and LULUCF) - reduced CH_4 or N_2O emissions and increased carbon sequestration

- Cover crops
- Rotational grazing – basic and intensive

For this preliminary list of BMPs, we used emission factors and activity data to calculate estimates of BMP GHG benefits and associated uncertainty. Details on methods and assumptions used for calculating GHG reduction factors and costs of adoption are included in this report and in the BMP database (see *BMP Activity and RF Database.xlsx*). Several of the evaluating criteria are based on qualitative scoring, which we scored using our expert knowledge, information from our literature review and feedback from AFF agrologists.

To demonstrate how stakeholders can engage with the MCF, we analyzed BMP rankings under three scenarios of different weightings for the 11 criteria depending on hypothetical stakeholder priorities: 1) equal weighting of all criteria, 2) industry stakeholder with priorities in adoptability criteria, and 3) public stakeholder with priorities in GHG and environmental co-benefits. We also tested two more scenarios using public stakeholder criteria weighting: 4) a scenario where uncertainty in performance scores is unimportant, and 5) we used hypothetical adoption levels that varied by BMP. For these analyses we assessed all BMPs from the preliminary list at an aggregated level (e.g., all cropland for total GHG benefits). All BMPs were analyzed assuming 50% adoption would be achieved by 2030 (i.e., the BMP is applied to 50% of all potential activity units), except for scenario (5) where adoption levels were purposely varied across the BMPs. A summary of the results of these sensitivity and scenario analyses are provided in the table below.

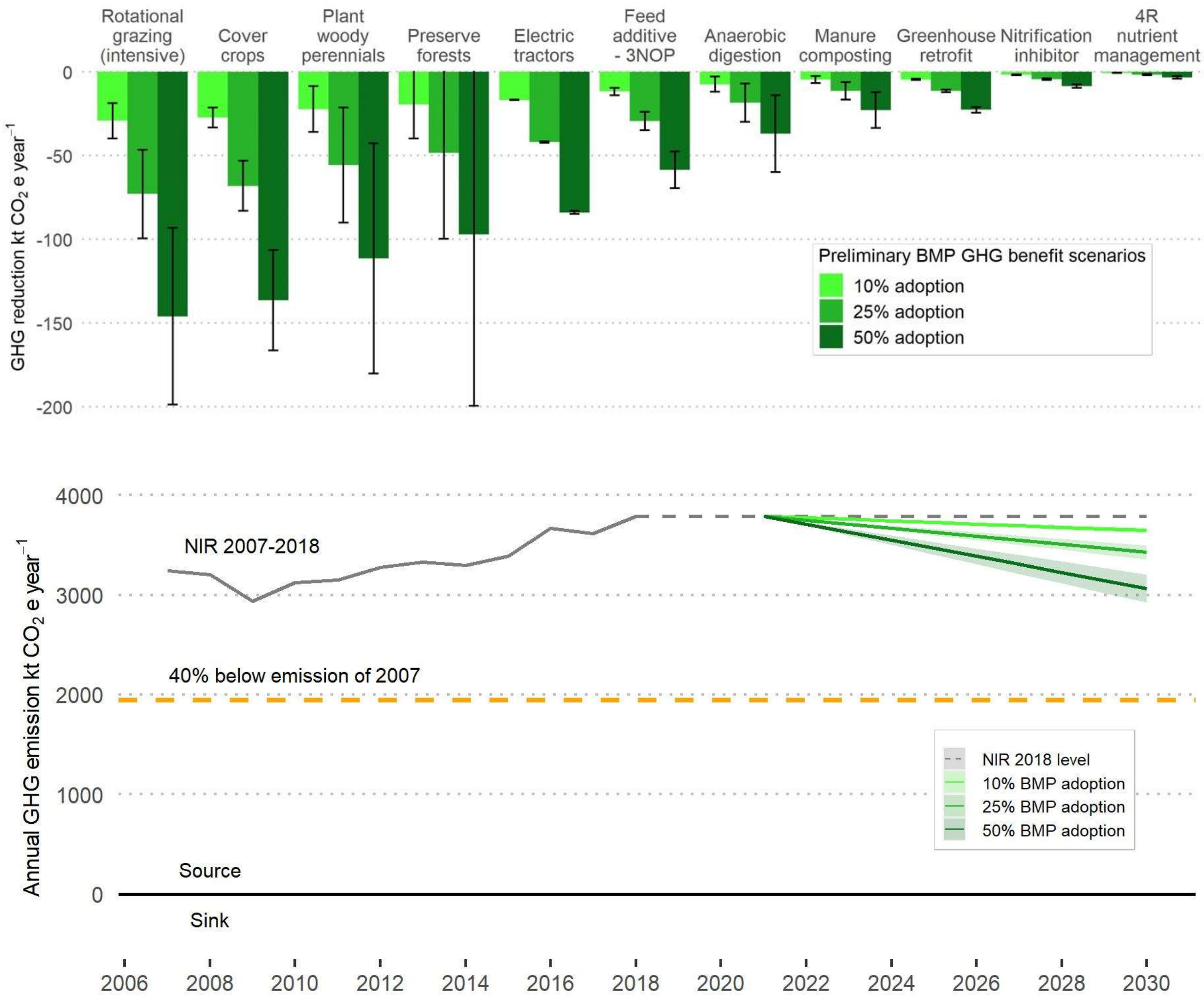
Comparison of top-five ranking BMPs across five different criteria weighting scenarios.

Ranking	**Scenario 1: Equal weights**	**Scenario 2: Industry stakeholder**	**Scenario 3: Public stakeholder**	**Scenario 4: Public stakeholder ***	**Scenario 5: Public stakeholder ***
	50% adoption level				Theoretical adoption rates (**Table 7**)

1	Cover crops	Cover crops	Cover crops	Preserve forests	4R nutrient management / Cover crops
2	Preserve forests	4R nutrient management	4R nutrient management	Greenhouse retrofit	Greenhouse retrofit
3	Plant woody perennials	Plant woody perennials	Greenhouse retrofit	Cover crops	Feed additive – 3NOP
4	4R nutrient management	Preserve forests	Plant woody perennials	Plant woody perennials	Preserve forests
5	Greenhouse retrofit	Nitrification inhibitor – DCD	Preserve forests	Anaerobic digestion	Nitrification inhibitor – DCD

Several BMPs were ranked highly across all tested scenarios. The ‘cover crops’ BMP consistently ranked highly (first, second, or third). Next, the BMPs ‘preserve forests’, ‘4R nutrient management’, and ‘plant woody perennials’ ranked in the top five in all scenarios where they were included. Of note, three of these top BMPs (‘cover crops’, ‘preserve forests’, and ‘plant woody perennials’) are associated with GHG benefits from C storage in soils and woody biomass, which are accounted for in the LULUCF inventory sector. Importantly, while emissions from land conversions (afforestation and deforestation) are counted towards the provincial total, all other LULUCF line items (i.e. ‘land remaining’ / unconverted lands) are reported as memo items in the BC PI and not counted in the provincial total.

The BMPs ‘feed additive – 3NOP’ and ‘greenhouse retrofit’ ranked highly under scenarios under our public stakeholder scenario with criteria weighted to prioritize GHG and environmental co-benefits. In contrast, when industry stakeholder criteria weightings were used in scenario (2), the BMP ‘nitrification inhibitor – DCD’ was in the top five. It is important to note that these scenarios simply reflect differences in how the criteria weightings can be changed (and in scenario (4) – how uncertainty weighting can be changed). These do not reflect how rankings would change with varying levels of adoption potential that may be more realistic for each BMP, as all of these BMPs were included with an assumed 50% adoption level (except for scenario (5)).



Potential GHG benefits for targeted BMPs at three levels of adoption individually and a combined total, relative to reductions from 2018 emissions to meet the 2030 emission reduction target (40% below 2007 emissions).

We also evaluated the GHG benefit potential of the preliminary BMPs at an aggregated level. We did this at three adoption levels, 10%, 25%, and 50%. The figures above illustrate i) potential GHG benefits by individual BMP and ii) the combined emission reductions relative to 2018 emissions. We estimate that reaching a 50% adoption level for all the BMPs included in this analysis would result in an annual GHG benefit of -718 (± 132) kt CO_2e year^{-1}, which is only a 5% reduction in emissions relative to 2007. In comparison, with a more achievable adoption level of 25%, GHG benefits are estimated as -359 (± 66) kt CO_2e year^{-1} which would nearly offset the increase in emissions since 2007. In these coarse-level preliminary estimates, overall GHG benefit potential is driven by potentially large carbon sinks in soils and vegetation from rotational grazing, cover crops and tree-planting near riparian waterways, all of which have important co-benefits.

Included with this report are the equations and data sources used to calculate BMP GHG benefit potentials and determine criteria scores, and instructions to use the MCF Excel tool. We conclude the report with a set of four major recommendations:

1) **Increase expert and stakeholder involvement:** Future analysis can add new, or refine existing, BMPs and associated performance data into the BMP database for improved decision-making analysis. This should include experts from various stakeholder groups.
2) **Expand BMP database:** An expanded literature review will improve the analysis of a wider range of BMPs. Additional empirical or modeled data will likely be required. Priority should be placed on reducing the uncertainty on these “high-risk but high-return" BMPs, such as planting and conserving woody perennials (trees and shrubs) on agricultural land. We recommend further collaboration and integration with groups like Farmers for Climate Solutions to capitalize on important synergies with national BMP development and accounting efforts, and developing a more robust BMP database and the appropriate online infrastructure to house it.
3) **Incorporate temporal and spatial components into the analysis**: Another important next step would be to incorporate an approach that better reflects the temporal and spatial-explicit performance of the BMPs in calculations of emissions benefits and aggregated reporting. Many of the BMPs that are appropriate for BC agriculture vary in their performance over time, by soil type and by climate. Incorporating these components into BMP benefit calculations will help to reduce uncertainties and enable a more realistic assessment of BMP options. Enabling BMP benefits to be aggregated geographically would also enable a comparison of BMP performance within a region to determine which BMPs are best suited for local conditions and commodities. Alternatively, spatially explicit data could be used to prioritize regions across the province for BMP investment. A regional approach would lead to more accurate GHG benefit estimates.
4) **Develop a measurement, reporting and verification approach:** For agriculture to contribute meaningfully to provincial emissions targets by 2030, BMP programing

will have to be rolled out widely as soon as possible. It is imperative that as this programming is developed it includes a robust measurement, reporting and verification (MRV) approach. Given our lack of empirical data on BMP performance specific to BC, an MRV approach is required to ensure that anticipated GHG benefits are actually being achieved and can be credited for emission targets. Data also need to be collected to better quantify BMP environmental co-benefits and adoptability in BC for decision-making based on evidence that is specific to BC. As more regional-specific empirical data become available, BMPs can be re-assessed and re-prioritized using the MCF. Developing an effective MRV approach within a timeframe to meet 2030 emission targets will require large amounts of resources that will need to be mobilized immediately.

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Table of Abbreviations

AAFC	Agriculture and Agri-Food Canada
AFF	British Columbia Ministry of Agriculture, Food and Fisheries
AFF-CAT	AFF – Climate Action Team
BC	British Columbia
BMP	Beneficial management practice
EFP	Environmental Farm Plan
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
CH_4	Methane
FCS	Farmers for Climate Solutions
GHG	Greenhouse gas
LULUCF	Land use, land-use change, and forestry
MCA	Multi-criteria analysis
MCDA	Multi-criteria decision analysis
MCF	Multi-criteria framework
NIR	National Inventory Report
N_2O	Nitrous oxide
PI	Provincial Inventory
UBC	University of British Columbia

1. Introduction

Meeting the provincial target of greenhouse gas (GHG) emission reductions of 40% by 2030 from 2007 levels is a challenging but imperative task. Although estimated to be a relatively small contributor to British Columbia's (BC) GHG emissions (~ 5.4 %[1]) the agricultural sector has the potential to not only reduce emissions of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) gases but also to mitigate emissions through sequestration of CO_2. Recent analyses have demonstrated the potential for agriculture to play an important role in meeting Canadian emissions targets (Drever et al. 2021, Farmers for Climate Solutions 2021) and the federal government has committed substantive resources to support the development and deployment of beneficial management practices (BMPs) (Government of Canada 2021a, 2021b). While there are well-established BMPs that agricultural producers could adopt to help mitigate emissions, there are several knowledge gaps that need to be addressed in order to develop a successful mitigation strategy for this sector particularly in BC. The availability of accurate emissions data for BC's diverse agricultural products are limited, making calculations for potential mitigation strategies challenging, and with large associated uncertainties. Furthermore, consideration of key co-benefits and/or costs and constraints of BMPs are important in development of BMP programming, yet are challenging to collectively assess given different units, data sources, and uncertainty.

Agricultural practices can provide many additional environmental services beyond GHG benefits (GHG emission reductions + carbon sinks) such as improvements to soil, water, and air quality, and biodiversity. On the other hand, practices intended to reduce emissions and/or sequester carbon may result in undesirable outcomes, such as unintended direct or indirect GHG emissions that may partly or even fully offset those benefits. Finally, adoption of BMPs can impact producers in terms of, for example, yield, economic efficiency, and ability to adapt to a changing climate. Therefore, a systematic process of evaluating multiple criteria related to the

[1] Figure includes emissions categorized in the Agriculture, Energy and Land use, land-use change, and forestry sectors. For details of these emission see *Report 1: BC Agriculture GHG Emission Profile Analysis*

costs and benefits resulting from implementing a BMP should be included in strategic decision making on GHG abatement programming.

1.1. Multi-criteria frameworks for decision making in the BC agriculture sector

Multi-criteria frameworks are used for a wide range of decision making, including those related to adapting to and mitigating climate change[2]. There are, to our knowledge, two previous projects using MCF approaches to assess BMPs for agricultural climate change mitigation and/or adaptation in BC.

In one example, *Integration of Agricultural Climate Change Information Into EFP Resource Materials*, BMPs in the Environmental Farm Plan (EFP) program were assessed for multiple criteria, including GHG benefits (Powell 2018). Criteria included climate change mitigation and adaptation, and environmental co-benefits: biodiversity, erosion, air quality, integrated pest management, nutrient management planning, riparian, and water quality. Mitigation and adaptation criteria were qualitatively assessed on a discrete scale of 0 to 3 and environmental co-benefit criteria on a binary scale (0 or 1). Evaluation consisted of discrete choices, such as: "adopt", "adapt" with additional information or change to the BMP, or "reject" if it was not suitable or practical (Powell 2018). This entirely qualitative approach provides an extensive list of BMPs applicable to various sectors. However, to make strategic investments in BMPs for provincial-level goals, such as meeting GHG reduction targets, and/or for making discrete choices between BMPs, decision makers and producers should be able to rank BMPs' performance in relation to one another. An example of this approach is seen with the GHG and Carbon Sequestration Ranking Tool developed by the United States Department of Agriculture (USDA) that qualitatively ranks more than 30 BMPs in terms of carbon sink performance (United States Department of Agriculture n.d.).

In a second BC example, *BC Farm Practices & Climate Change Adaptation*, six BMPs were evaluated across seven criteria: effectiveness, economic efficiency, flexibility, adaptability, institutional compatibility, adoptability, and independent benefits (Dobb 2014). Scores from 1-5

[2] MCF frameworks have been used for decision making in the management of, for example, forests, urban water, and marine protection areas, and in responses to infectious diseases (e.g. Cohen et al., 2019; Cox et al., 2013; Doukas and Nikas, 2020; Noble and Christmas, 2008; Shackelford et al., 2019).

for each BMP outcome were coded from farmer interviews and the weighted importance of each criterion were calculated from farmer rankings. While this approach evaluated a limited number of BMPs, it provided overall scores for BMPs relative to one another following a synthesis of stakeholder input.

While there has been some BMP evaluation for BC agriculture, the Ministry of Agriculture, Food and Fisheries Climate Action Team (AFF-CAT) identified a clear need for further guidance in their development of BMPs to contribute to GHG emissions reductions. They sought a framework that would use a systems approach to quantify and understand the relative importance and trade-offs of economic and environmental costs and benefits of a range of conventional and promising new agricultural practices and technologies in BC's agricultural sector. For long-term viability, this framework would be transparency in the quality of available input data (e.g., uncertainty in GHG benefits) and in the valuation of a suite of diverse criteria that are used to quantify the overall outcomes of GHG mitigation scenarios.

1.2. Report objectives and approach

This is the second of three reports prepared by the Sustainable Agricultural Landscapes laboratory at the University of British Columbia as part of the project *Opportunity Assessment of Agricultural Greenhouse Gas Reductions and Carbon Sinks.* The overarching objective of this report is to summarize progress towards the development of a multi-criteria framework (MCF) that can be used to collectively assess GHG benefits, environmental co-benefits, and adoptability considerations of BMPs. This work is intended to support the development of agricultural BMPs that can help meet GHG reduction targets. The specific objectives of this project report work are to:

- Assess options, establish protocols, and facilitate an iterative design for an MCF tool with long-term utility
- Review a shortlist of potential BMPs and catalogue their GHG benefits and co-benefits
- Identify a preliminary set of BMPs to demonstrate the utility of the MCF tool
- Develop a set of methods for quantifying BMP GHG benefits and build a simple database that can be integrated easily into the MCF tool
- Demonstrate the MCF tool's capabilities to evaluate this preliminary set of BMPs and estimate their potential contribution to GHG emission reduction targets

Consultation with members of AFF-CAT was conducted at the start of the project and during dedicated meetings on MCF objectives, functionality, and short- and long-term utility, along with consideration of pre-established objectives and questions presented by AFF-CAT. From these discussions with AFF-CAT we identified that an MCF will be most useful to them if it:

1. can be consistently used within AFF with limited training
2. is transparent in methodology, data sources, and calculations
3. is functional for different users
4. can be integrated with data sets to avoid manual changes that are labour intensive
5. can be easily modified to include or exclude criteria as data availability and needs change
6. provides ranking output of best BMP options
7. includes some measure of uncertainty in GHG emissions as a defining criterion
8. can be used to identify best options for further investigation, or where gaps in data exist for future decision making
9. provides options for key criteria with thresholds of acceptability (e.g., cost) to identify if a BMP should be considered or not
10. can generate visual outputs for intuitive interpretation and communication material for non-experts
11. be sufficiently modular to allow the integration of additional criteria
12. allow for outputs that can potentially be used for larger-scale frameworks and comparison with existing frameworks.

We incorporated these needs in developing an MCF built in Microsoft Excel (MCF Excel tool: *BC MCF Tool.xlsx*) and in this report we detail methodology and results from our preliminary implementation.

2. Using an MCF for decision making

2.1. General overview

The broad purpose of using an MCF, or more explicitly, when completing a multi-criteria analysis (MCA), is to provide a systematic assessment of choices, options, or alternatives in meeting a specific objective based on criteria established as important by relevant stakeholders. Outputs from MCFs can rank options for a decision-making objective, identify preferred option(s), or accept or reject options. Thus, MCF outputs can support decision making in a range of ways from identifying a single discrete choice to identifying a few options for more detailed assessments. MCF techniques can include assessments of the non-financial value of different options to achieve a predefined objective, which distinguishes it from monetary-based analyses such as cost-benefit analysis and cost-effectiveness analysis. A common practice for MCF techniques is a performance matrix in which each row describes an option (i.e., BMP) and each column describes a criterion that is deemed important to evaluate the performance of the options. Subsequent steps in the analysis largely define differences among MCF approaches and techniques.

A few examples of approaches and techniques to conduct an MCA, include Analytical Hierarchy Process, Integrated Analysis Models, Multi-Criteria Decision Analysis (MCDA), Multi-Attribute Utility Theory, Strategic Environmental Assessments, and Fuzzy Cognitive Maps (Cohen et al., 2019; Cox et al., 2013; Doukas & Nikas, 2020; Shackelford et al., 2019). Notably, the development of MCF methodology is shaped by i) the type of data used: quantitative vs. qualitative, ii) how scoring and weighting of criteria is done, and iii) in the tabulation of all criteria scores for an overall performance score of each option. A MCDA approach was deemed appropriate for the requirements identified for this project as it can handle both quantitative and qualitative data, allows for flexible scoring, and supports a weighted linear equation to calculate overall BMP performance scores. The MCDA is commonly used as a decision-making guide rather than to provide the decision (Lai et al. 2008, Cohen et al. 2019), thus, would be of use to AFF-CAT for identifying top-performing BMPs for more detailed modelling and analysis.

2.2. Steps to developing an MCF

In this section we provide a brief introduction to the steps taken in developing an MCF, specifically an MCDA. Then, in the following section (**3. MCF Implementation Methods),** the methods for this project are described in relation to these steps.

2.2.1. Define objectives

A critical aspect of MCF development is that the tool is designed specifically to meet the needs of the user and to inform decisions in a way the is most informative to them. A clearly defined objective is required prior to selecting the BMPs to assess, the criteria to assess them with, and the approach to scoring and weighting. The objectives used in this project for MCF development are outlined in section ***3.1. MCF objective and sub-objectives***.

2.2.2. Select options to be evaluated

Options or alternatives are identified that can contribute to meeting objectives – the ‘options’ being analyzed in this project are BMPs. All stakeholders can be involved in conceiving and developing the BMPs such that there is potentially a long list of BMPs that could contribute to meeting the project objectives. However, it is important to short-list and streamline the most sensible options, prior to thorough review and data compilation, given the quantity of work required to gather quality data across all criteria for each BMP being evaluated. BMP selection in this project is discussed in section ***3.2. BMPs***.

2.2.3. Select evaluating criteria

Criteria should explicitly evaluate options (i.e., BMPs) in terms of the main decision-making objective and their definitions should promote objectivity in scoring. Criteria of interest can be represented in a value tree of main objectives and associated sub-objectives (example from this project shown in **Figure 1**). This step is useful in identifying potential areas of conflict or trade-offs in key objectives. Grouping criteria allows for subsequent steps in the performance matrix to calculate within- and across-group scoring and weighting, and can provide higher-level comparisons of grouped criteria (e.g., overall environmental benefits vs. adoptability), if desired.

Selected criteria should be checked to ensure performance independence among criteria. A quick check for this is to test if scores for a BMP can be assigned on one criterion without knowing what the BMPs’ scores are on any other criteria. Redundancy in criteria leads to ‘double counting’ an outcome (e.g., yield and income benefits) and should be avoided. The final selection of criteria used in the analysis is also largely based on which criteria are presently feasible to assign an outcome. However, the flexibility in the approach will allow additional criteria to be included in the future when more data become available or priorities change.

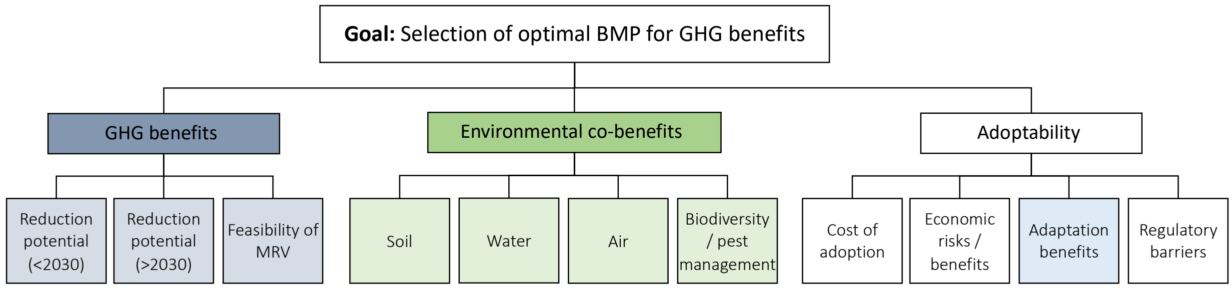

Figure 1. *Value tree for criteria selection in this project.*

2.2.4. Score options within criteria

The performance score of each BMP within each criterion is inputted by the user. The performance score for a BMP within a criterion represents preference for an outcome in meeting the overall objective and can be quantitative or qualitative (e.g., categorical or binary). Performance scores are standardized to be comparable across criteria; this avoids adjusting criteria weighting (see section ***2.2.5. Weight criteria***) when BMPs are added with outcomes that are substantially different (i.e., quantitative data, which can be measured or evaluated using different approaches or different units, or qualitative data from different scales), which could result in a criterion having an overly dominant effect on a BMP's final score. A common method to standardize scores is to use a scale of 0 to 100 assigned in relation to the best possible outcome for that criterion – this standardizes the outcomes to be unitless (Belton and Stewart 2002). For best results, scoring should be checked to ensure that the range of outcomes of a criterion are not biasing the results; for example, by comparing how changes on one scale compare to the magnitude of changes on another scale.

In MCDA, 'external uncertainty' refers to the lack of knowledge regarding the real-world performance of each of the options being evaluated (Belton and Stewart 2002). There are varying levels of uncertainty associated with the performance of a given option within each criterion, and this uncertainty cannot be controlled by the decision maker. For example, it can be due to a lack of knowledge or data related to the BMP's performance or may be related to known and inherent randomness in the performance of the BMP in the real world. The simplest method to account for this type of uncertainty in MCDA is to include a formal assessment of the performance uncertainty as another criterion in the analysis (Belton and Stewart 2002). The approach to uncertainty scoring used in this analysis is discussed in **Section**

3.4. Scoring BMPs in selected criteria.

2.2.5. Weight criteria

Selected criteria are weighted according to expert opinion based on their relative importance in achieving the objective. Criteria weights are easily changed, should reflect the objectives of a given analysis, and should consider 1) the range of differences among the BMPs and 2) how much that difference matters (Odu 2019). There are several approaches to determining the relative importance of each criterion such as simple step-wise ranking of the importance of each criterion, expert allocation of percent importance of each criterion, or using a pairwise comparison matrix for expert decisions on all paired combinations of criteria (Stillwell et al. 1981). Methods proposed for criteria weighting in this project are described in **Section *3.5. Criteria weighting in the MCF***.

2.2.6. Calculate final scores

In MCDA the final score for a given alternative or option (i.e., BMP) being assessed is a combination of its score within each criterion and the relative weights of those criteria. Most commonly, the total score of an option is determined by multiplying its performance score within a criterion, by the weight of that criterion, and then adding these values together across all criteria (Belton and Stewart 2002). This simple function is referred to as a 'weighted linear equation' and has been used in decision analysis frameworks for similar objectives (e.g., Shackelford et al. 2019). An important property of this additive approach is that it allows for trade-offs amongst criteria, such that high scores in one criterion can offset low scores in another (Belton and Stewart 2002). This trade-off property highlights the importance of analyzing model output to see where trade-offs may be occurring in order to assess if they are acceptable or desirable given the project objectives (discussed for this project in **Section *3.6.2. BMP ranking and graphic outputs***). Further details of how final scores are calculated in the MCF in this project are discussed in **Section *3.6.1. Calculating final scores***.

2.2.7. Final ranking and graphic outputs

For the final output, all of the options being assessed are ranked based on their final score. It is common and informative to determine scores and ranking at intermediate levels as well, such as for criteria categories (Belton and Stewart 2002). However, these intermediate and total scores and rankings are not the end of the analysis. Aggregated scores simply reflect a summary of the value judgements that have been made (i.e., criteria selection and weighting) and an assessment of the potential performance of the selected options (BMPs) within these evaluating criteria. Therefore, it is important to consider the "profile" of the total score for each BMP, to understand where the score is coming from (Belton and Stewart 2002); for example, to consider what the strengths and weaknesses of the top-ranked BMPs are. Options with similar final scores could have very different trade-offs (Belton and Stewart 2002). Inspection of final scores and visual output can also be important to identify gaps in the evidence (Shackelford et al. 2019), if the output is displayed in a way conducive to this. Final scores can be illustrated using simple techniques such as bar graphs or radar-grams. Graphical outputs for this project are illustrated in Section ***3.6.2. BMP ranking and graphic outputs.***

3. MCF Implementation Methods

The MCF we developed operates in Microsoft Excel, which makes it broadly functional for a range of users, transparent in how data and outcomes are used/calculated, and offers flexibility for future development and iterative changes as data become available. Our MCF is transparent in design to show how criteria, chosen and defined in consultation with AFF-CAT, are used in the analysis to rank preliminary BMPs, and the underlying mechanics of scoring, weighting, and outcome calculations. Brief written instructions included in this report, plus video recordings of MCF use, will allow future users to update the MCF as more data become available. In the next sections, we outline the main steps in the development and implementation of the MCF for this project.

3.1. MCF objective and sub-objectives

The objective of this MCF is to help identify BMPs that offer the most opportunity for GHG benefits[3] at the provincial level, while also considering environmental co-benefits and adoptability for producers and/or industry. The overall performance of each BMP in relation to each other provides guidance in deciding which BMPs merit further attention for developing and/or enhancing BMP programming in BC. In addition to overall performance rank, key outputs of this MCF analysis include total GHG benefit potential in the province (kt CO_2e) and the cost (i.e., producer and/or government spending on BMP adoption) per unit of GHG benefit. The level of uncertainty associated with each BMP performance assessment is also calculated. Thus, the MCF can also be used to help target BMPs that may have large potential benefits but are too risky to invest in given their uncertainty and/or lack of data, making them candidates for future research.

3.2. BMPs selected for MCF analysis

We developed a shortlist of BMPs appropriate for BC agriculture and made preliminary estimates of their GHG benefits in order to assess and demonstrate the function of the MCF tool in BMP decision making and provide rough estimates of the sector's emission reduction potential. BMPs included in this analysis are practices and technologies with known GHG reduction or CO_2 sequestration potential, such as adoption of farm technologies, changes in nutrient management practices, shifts in cultivation practices, and changes in land use. Through a limited review of the scientific and grey literature, we first populated a BMP literature database with key information on BMPs. In this database we catalogued details of published studies including the GHG reduction factors of the BMPs and any relevant information available for assessing BMP costs or co-benefits. The database was submitted along with this report as an MS Excel file: *BMP Literature Database.xlsx.*

From this literature database we then selected a preliminary set of BMPs based on a combination of factors: potential to mitigate GHG emissions from the largest subcategories of

[3] GHG benefits are the net CO_2, N_2O, CH_4 emission reductions plus CO_2 sequestration (carbon sinks)

agricultural emissions (see *Report 1: BC Agriculture GHG Emission Profile Analysis),* BMPs that could be applied across BC's diversity of production systems, expert knowledge on documented viability of BMPs for lowered GHG emissions in BC, and the availability of peer-reviewed and published GHG benefit data. Thus, we selected BMPs related to the emission subcategories "enteric fermentation", "organic fertilizers", "synthetic fertilizers", "manure management", "stationary combustion", "on-farm transportation", and "forestland converted to cropland", given their relatively high contributions to total agricultural emissions in BC.

We also drew on the list of BMPs identified by Farmers for Climate Solutions (FCS) who developed national-level assessments of optimal BMPs for climate change mitigation while considering other environmental, economic, and social objectives (Farmers for Climate Solutions, 2021). The BMPs included in this preliminary work are listed in **Table 1** and were submitted as a separated database as an MS Excel file: *BMP Activity and RF Database.xlsx***.**

Table 1. *List of BMPs (and associated GHG benefit) used in our preliminary analyses.*

BMP	Description	GHG benefit
4R nutrient management (annual crops)	Choose the (1) right amount of the (2) right type of plant-available nutrients to apply at the (3) right time and (4) right place	Reduced N_2O
Anaerobic digestion: renewable biogas	Convert pretreated animal manure, food waste, and crop residue into biogas (60% CH_4 + 40% CO_2) to offset consumption of natural gas on farm	Reduced CO_2 and CH_4
Best-in-class greenhouse retrofit	Retrofit existing greenhouses with the current industry best practice for energy efficient technologies and operating practices, e.g. condensing boilers, LED grow lights, greenhouse envelope improvements, etc.	Reduced CO_2
Cattle feed additive: 3NOP	Adding feed additive: 3-nitrooxypropanol to cattle feed	Reduced CH_4
Cover crops	Fall-planted cover crops for major annual field crops	C sequestration in soil and reduced N_2O
Manure composting	Aerobic composting using the passively aerated windrow method	Reduced CH_4
Nitrification inhibitor: DCD	Addition of dicyandiamide during application of synthetic fertilizer on cropland in order to sustain the nitrification process in soil	Reduced N_2O
Plant woody perennials	Planting perennial woody species along the perimeter of agriculture fields or as riparian buffers either in the agricultural land reserve or in pastureland	C sequestration in woody biomass and soil*

Preserve forest from conversion to cropland	Preventing forest from being converted to cropland	Avoided CO_2, N_2O emissions
Replace diesel tractors with electric	Replace diesel tractors on farms with electric or hybrid tractors.	Reduced CO_2
Rotational grazing (basic)	Animals are rotated through each of multiple paddocks once and grazing is deferred in each paddock over years for critical vegetation growth period to maintain good pasture condition	C sequestration in soil and reduced CH_4
Rotational grazing (intensive)	7 or more paddocks with less than 10 days grazing duration per paddock. Duration between grazing on each paddock is based on sufficient time to reach desired vegetation stated for long-term vegetation health	C sequestration in soil and reduced CH_4

* Soil carbon sequestration in riparian buffers located in pasture lands is assumed to be the same as areas without the BMP and thus has no emission reduction factor.

3.3. Selected criteria for project goals

Criteria included in the MCF Excel tool are described in **Table 2**. Criteria grouping and individual criterion have been developed in collaboration between UBC and AFF. The GHG benefit criteria have been primarily developed by the UBC team, in consultation with the AFF working group. The environmental co-benefits and adoption criteria were primarily developed and proposed by AFF, based on goals of CleanBC, given that a primary objective of this project is to allow AFF to answer these policy analysis questions. Of the eleven chosen criteria, two criteria are assessed quantitatively: GHG benefits (<2030) and cost of adoption, and all other criteria are evaluated on qualitative scales. Each criterion requires a performance score and an associated uncertainty score.

Table 2. *List of criteria selected for this analysis. Performance scores within criterion can be qualitative (QAL) or quantitative (QNT). The specific qualitative categorical scale (A-E) used to score criteria is indicated for QAL criteria only, while the uncertainty score is for either QAL or QNT.*

Category	Criteria	PS	QAL Scale	Uncer-tainty *	Definition
GHG Benefits	Short-term (<2030) GHG benefit potential	QNT	n/a	QNT	Annual GHG benefit potential (emissions reduction or C sequestration) associated with implementing a practice, up to 2030

Category	Criteria	PS	QAL Scale	Uncer-tainty *	Definition
	Long-term (>2030) GHG benefit potential	QAL	A	QAL	GHG benefit potential (emissions reduction or C sequestration) associated with implementing a practice, beyond 2030
	Measurement, Reporting, and Verification (MRV) feasibility	QAL	B	Not included	Ability to implement a MRV system to track GHG benefits of a management practice
Environmental co-benefits	Soil quality	QAL	C	QAL	Increased nutrient cycling, soil organic matter, soil moisture retention, water infiltration and/or reduced erosion
	Water conservation/quality				Reduced water use, or reduced contribution of dissolved oxygen, phosphorus, nitrates, nitrites, fecal matter, sedimentation, chemicals, and/or heavy metals in bodies of water
	Air quality				Reduced production of ammonia, oxides of nitrogen, sulfur oxides, particulates, odors, and other airborne toxins
	Biodiversity / pest management				Increased plant or animal diversity on the farm, increased wildlife corridors or pollinator and/or beneficial organism habitat
Adoptability	Cost of adoption	QNT	n/a	QAL	All monetary expenses incurred with adoption and on-going use of the management practice; the scaled score is based on cost of adoption divided by emission reductions ($ CAD Mg CO_2e^{-1})
	Financial risks / benefits	QAL	B		1. The potential to unintentionally reduce farm production, in terms of crop yield, on-farm feed production for livestock, or reduced egg, meat, or milk output, or in contrast, 2. Costs saved or extra income generated, regardless of the cost of

Category	Criteria	PS	QAL Scale	Uncer-tainty *	Definition
					adoption. Excludes cost savings incurred elsewhere, i.e. by society or otherwise
	Adaptation	QAL	B		Increased overall resilience of the farm to impacts of climate change, such as: drought/moisture deficit, flooding, wildfires, changing pests, extreme storms / other weather events, and/or provision of season extension benefits
	Regulation barriers	QAL	D		Any extra steps required to implement a practice, directly or indirectly, due to current regulations / legislations. Includes direct barriers such as paperwork and waiting periods for permits or approvals, or indirect barriers such as extra time spent on additional reporting or tax requirements.

*Qualitative uncertainty is evaluated using Qualitative Scale E

3.4. Scoring BMPs in selected criteria

For each criterion, each BMP is assigned a performance score and an associated uncertainty score; the uncertainty score is an estimation of the uncertainty in the performance score. 'Local scoring' is used for all quantitative data, such that a scale of 0 to 100 is assigned in relation to the best possible outcome for that criterion – this standardizes the outcomes to be unitless. All qualitative data are standardized to be unitless as well, but instead using 'global scoring' which assigns pre-defined (i.e., global) scores to each of the five levels of performance outcomes (based on five-point categorical scales).

3.4.1. BMP database and MCF integration

The BMP Activity and RF Database (*BMP Activity and RF Database.xlsx.)* described above is used to populate the quantitative data required for the MCF. The quantitative data compiled in the 'BMP database' tab of this database pulls data from various tabs that contain details for individual BMPs. The data compiled for each BMP includes: GHG emission reduction factors and associated uncertainty, total activity units, the maximum biophysical potential. We set up the database to be distinct from the MCF tool to enable ongoing BMP development without impacting the utility of the MCF. When a set of BMPs are ready for analysis they can be copied from the 'BMP database' tab in the *BMP Activity and RF Database.xlsx* file, into the 'BMP database' tab in the MCF Excel tool (*BC MCF Tool.xlsx)*, and these data will then auto-populate the MCF performance matrix when selecting BMPs from a dropdown menu.

Data sources used to populate quantitative data in the BMP database were largely from Agricultural Census data (Statistics Canada n.d.) for activity data (e.g., land area under cultivation, total number of cattle), Canada's National Inventory Report (NIR) for emission factors, and the FCS report (FCS, 2021) for emission factors and cost of adoption. When needed data were not included in those sources, we used primary and secondary literature to estimate these values. The general approach to these calculations is described in the next section (3.4.2), while specific GHG emission reduction calculations and assumptions for each BMP are included in the database and summarized in the Appendix. The extensive data compiled in the literature review can be useful in informing scoring of qualitative criteria, which is described in section 3.4.3. The BMPs have been compiled by particular commodity or sector whenever possible (e.g. potato or beef cattle) and by emissions category (e.g. cropland remaining cropland, N_2O). We have also aggregated the BMP outcomes by sub-category (e.g. combing all crop or animal types) and emissions category (i.e. all greenhouse gas sources and sinks) for a total emission benefit. This enables the user to compare BMP GHG performance at varying resolution.

3.4.2. Quantitative scoring in the MCF

Quantitative data was collected and compiled in the BMP database to provide realistic estimates of GHG benefits that could be achieved for a BMP and its implementation cost for a user determined level of adoption. We did this in the context of meeting provincial emissions targets by 2030 and thus standardized these quantitative data for the eight-year (2022 to 2030) period in which the target emission reductions can be achieved. Two assumptions / procedures used in this analysis for the two quantitative criteria (short-term GHG benefit potential <2030 and cost of adoption) are that:

1. After implementation, BMPs remain in use in perpetuity, or in the case of technology, until the end of useful life.
2. All quantitative data are time-averaged values on an annual basis.

The performance outcome for the short-term GHG benefit potential (<2030) criteria is calculated by multiplying the BMP GHG reduction factor (kt CO2e activity unit-1 year-1) with the potential activity units for BMP uptake. The methods for determining these two components are explained below.

The total number of activity units used for determining emission benefits for each BMP is calculated by multiplying the estimate of adoption potential (%) determined by the MCF user by the maximum biophysical potential activity units associated with the BMP. The maximum biophysical potential is the maximum number of activity units a BMP could be applied to based on total reported numbers (e.g. total number of animals or hectares of a given crop), biophysical limits / environmental constraints (e.g. cover crops cannot be grown for some regions of the province), or a combination of these two. Biophysical limits were determined using available Statistics Canada data, literature, and expert opinion. While adoptions rates can be set independently as a percentage of the maximum potential by the MCF user, in the analysis we present below we evaluated a range of adoption rates that were set to be consistent across a number of BMPs (10%, 25%, 50% adoption). A user could alternatively compare the GHG benefits of a single BMP under different adoption levels, which we illustrate in section 5.

Finally, the (quantitative) performance score for the potential GHG benefit criterion is calculated by multiplying the GHG reduction factor by the number of available activity units. The uncertainty associated with the GHG reduction factor is also recorded. The general data sources, components, units, and final calculations are summarized in **Table 3**, and are described in more detail in the Appendix. These data are summarized in our BMP literature review Excel file: *BMP Literature Database.xlsx.*

Table 3. *Summary of data sources, uncertainty propagation, and calculations for the GHG benefit (<2030) criterion.*

Sub-criterion	BMP GHG **reduction factor**		**Maximum potential activity units** for BMP uptake	**Adoption potential**	**potential GHG benefits**	
Data Source	Literature review		StatsCan, literature and expert opinion	MCF user	= a * c * d	= b
Component	a. reduction factor	b. uncertainty: standard error (fractional)	c. potential activity units	d. expected maximum adoption rate over 8 years	potential GHG benefits	uncertainty
Units	CO_2e / activity unit	%	# activity units	%	CO_2e	%

Cost of adoption data are also included in the BMP database and are automatically populated when a BMP is selected in the MCF. The cost of adoption includes all costs (capital and operational) and is expressed in $CAD / activity unit / year. Unlike the short-term GHG benefit potential <2030 associated with BMPs, which we assumed for are implemented in 2022 and are continued in perpetuity (or until end of useful life for technology upgrades), we calculated cost of adoption only from 2022 to 2030. This provides a rough comparison between BMPs, as this period also allows accounting for both upfront costs, and operational costs over the first few years without introducing the complexity of longer-term discount rates. Cost of adoption data are detailed further for specific BMPs in the Appendix.

3.4.3. Qualitative scoring in the MCF

For criteria that are scored qualitatively, the use of expert knowledge and/or assessment of literature is required. The MCF user(s) determine the scores based on a qualitative scale which assigns a numerical value to pre-defined outcomes. We have set these scales to be consistent in direction and range of options such that higher scores reflect preferred outcomes. Four different, five-point, categorical qualitative scales were developed for use with the different qualitative criteria and are provided in **Appendix B – Qualitative scales** and also in the 'Qualitative Input' tab in the MCF Excel tool. For most of the qualitative criterion, the MCF user is also required to assign an associated uncertainty score which indicates the level of confidence in the scoring of that criterion; this uncertainty scale is also outlined in the appendix. A prototype structure for averaging qualitative scores across multiple experts is included in the MCF Excel tool, with a separate tabs 'Qual_input_1' through 'Qual_input_6' included for 6 "users" to provide qualitative scores for the BMPs included in the analysis.

3.4.4. Missing data

Some BMPs might not have supporting data for environmental or adoptability co-benefits. If data is missing for these criteria, the BMP should be assigned a neutral performance score (=50) and a very high uncertainty score (=0) (see **Appendix B – Qualitative scales** for qualitative score descriptions). However, to function properly, the MCF relies on expert-generated data and the analysis should not be performed with substantial missing data. The MCF should only be used with BMPs that have data for all of the GHG benefit criteria.

3.5. Criteria weighting in the MCF

Criteria selected for inclusion are weighted by assigning their relative importance according to the opinion(s) of either a designated expert, a group of experts, or a group of stakeholders or some combination or these (see "Weighting" tab in the MCF Excel tool). Two approaches to assigning weights are included in this MCF: (1) A simplified approach of a step-wise ranking of the importance of each criterion and (2) expert allocation of percent importance of each criterion, either with or without a 'value-tree approach'. Instructions for inputting weighting in the MCF are included in **Section *4. Using the MCF: Workflow.*** For future analysis, surveys, workshops, or other data collection methods could be used to assess stakeholder preferences and assign weights.

To illustrate how BMP ranking would change with different weightings informed by contrasting stakeholder values, we developed three hypothetical stakeholder scenarios: 1) industry stakeholder; 2) public stakeholder; and 3) equal-weighted criteria. In scenario 1, it is assumed that industry would value a BMP in terms of direct benefit to their farm production systems, plus overall cost of adoption that the sector would need to absorb; in this scenario, the criteria weights are divided among six criteria: soil quality, biodiversity / pest management, cost of adoption, financial risks / benefits, adaptation benefits, and regulation barriers, and the remaining criteria are assigned weights of 0. In scenario 2, it is assumed that the public would value a BMP in terms of broader societal / public interest benefits; in this scenario, the weights are divided among the three 'GHG benefits', the four 'Environmental co-benefits' criteria, and two ‘Adoptability’ criterion: ‘cost of adoption’ and ‘financial risks /benefits. In scenario 3 (equal-weights), all criteria are assigned equal weighting. The weighting for these three scenarios are shown in **Table 4** and can be found in the MCF Excel tool ‘Weighting scenarios’ tab.

Table 4. *Summary of stakeholder criteria weighting scenarios.*

Criteria		1. Producer	2. Public	3. Equal
GHG BENEFITS	short-term GHG benefit potential	0.00	0.20	0.09
	long-term GHG benefit potential	0.00	0.20	0.09
	MRV feasibility	0.00	0.10	0.09
CO-BENEFITS	Soil quality	0.05	0.05	0.09
	Water conservation / quality	0.00	0.05	0.09
	Air quality	0.00	0.05	0.09
	Biodiversity / pest management	0.05	0.05	0.09
ADOPTABILITY	Cost of adoption	0.20	0.20	0.09
	Financial risks / benefits	0.30	0.10	0.09
	Adaptation benefits	0.10	0.00	0.09
	Regulation barriers	0.30	0.00	0.09
	SUM	1	1	1

3.6. Decision analysis and MCF outputs

3.6.1. Calculating final scores

As introduced in Section ***2.2.6. Calculate final scores***, a weighted linear equation is used to aggregate criteria scores within each BMP to provide a total score for the BMP. The performance score of a BMP for each criterion is multiplied by its criterion weight (see “weight” row in ‘MCF’ tab), and these weighted scores are then summed across all criteria for each BMP to calculate the overall performance score for the BMP. The same process is used for uncertainty scores; for each BMP, a weighted uncertainty score is determined by multiplying the BMP's uncertainty score within a criterion by the weight of that criterion, then all of the weighted uncertainty scores are summed within a BMP to give a total uncertainty score for the BMP. Finally, the uncertainty and performance scores are added to provide a total score for the BMP. This process is repeated for all BMPs, and then the BMPs are ranked based on their total scores (ranking and MCF output are discussed further in the following section). A summary and example of these calculations are provided in **Table 5**.

Notably, the additive aggregation method (commonly used in decision analysis for determining the total value of a given option being assessed) is used in this MCF both for tallying performance and uncertainty scores across criteria, as well as for combining those performance and uncertainty scores into one final score. A key function of this method is that it allows for trade-offs, such that performance scores and uncertainty scores can offset each other. For example, a low performance score can be compensated by a high certainty (low uncertainty) score, or vice versa. In case these trade-offs between performance and performance uncertainty are not desirable, we have included the option to weight the value of the uncertainty scores relative to the performance scores (see 'weighting' tab in the MCF Excel tool). The default uncertainty weight is set to 1, but this function allows the user to customize the analysis to a specific uncertainty weighting. For example, if uncertainty is only half as important as performance, then uncertainty weighting can be set to 0.5.

Table 5. *Steps to calculating the total score for a given BMP, starting with a performance score and uncertainty score within each criteria for a given BMP.*

Step	Description	Calculation	Example	Calculated Value
1a	Weight the BMP performance score by the weight of the criterion	Multiply the performance score (e.g., 75) by the weight of the criterion (e.g., 0.15)	75 * 0.15	11.25
1b	Adjust the uncertainty weight by the uncertainty weighting	Multiply the weight of the criterion (e.g., 0.15) by the weight of the uncertainty (e.g., 1)	0.15 * 1	0.15
1c	Weight the BMP uncertainty score by the weight of the criterion	Multiply the uncertainty score by the weight of the criterion	60 * 0.15	9

2a	Determine the BMP performance score	Sum the weighted performance scores for all criteria within this practice	11.25+12+9+10 +12.25+15+6+13	88.5
2b	Determine the BMP uncertainty score	Sum the weighted uncertainty scores for all criteria within this practice	9+8+8.25+7 +3+7+5.75+10	58
3	Determine the BMP total score	Sum the weighted performance and uncertainty scores for all criteria within this practice	88.5 + 58	146.5
4	Rank BMPs based on total scores	n/a		
5	Use BMP performance (2a) and uncertainty scores (2b) for graphic illustration of the results	n/a		

3.6.2. BMP ranking and graphic outputs

A performance matrix ("MCF" tab in the MCF Excel tool) holds the complete overview of criteria outcomes for each BMP. For the final output, the weights and scores for each BMP are combined to provide an overall score for each BMP and to rank from best to worst performing (highest to lowest score) according to selected criteria and weights. As shown in the "Results" tab, total performance score, total uncertainty score, overall score, and overall ranking of the top-5 BMPs are tallied. Additionally, separate overall performance rating, uncertainty rating, and combined rating (i.e. rating = fraction of full score) of each criteria group are tabulated. Results for the top 5 BMPs are displayed in three graphical outputs: (1) A biplot is used to synthesize and illustrate BMPs in terms of overall performance in relation to overall uncertainty, (2) a triangular radar graph is used to indicate the potential trade-offs between BMP outcomes in each criteria group, and (3) BMP benefit potential with error bars indicating quantitative uncertainty. These graphic outputs are generated on the 'Results' tab in the MCF Excel tool.

4. Using the MCF: Workflow

We have designed the MCF to be used in a series of steps that ideally include input from those who are likely to be involved with BMP related decision making as well as individual users interested in exploring output from the tool. **Table 6** outlines the steps for inputting data into the MCF tool.

Table 6. *Outline of workflow steps in the decision analysis using the MCF.*

Step	Task	Example of Input Source
1	**Determine criteria weights:** Survey stakeholders to establish relative value of each criterion, and prepare to input these values into the MCF Excel tool in Step (1a) (**Figure 2**). **Input weights:** Go to "Weighting" tab in the MCF Excel tool	AFF + Stakeholders
2	**Input weights:** 1. Enter criteria weights into column C 2. Enter uncertainty weight into cell P4	MCF User
3	**Determine qualitative scores for BMPs for each criterion:** Consolidate scores collected through expert opinion and survey of published data (as described in Steps (3a) and (3b), and prepare to input into the MCF Excel tool in Step (4) (***Figure 3***)	AFF + Industry + UBC
4	**Choose BMPs to assess** (***Figure 4***)	AFF + Industry
5	**Input BMP scores:** 1. In the 'MCF' tab – use the dropdown menu in column A to select a BMP. This will auto-populate the MCF with all quantitative data, except for adoption potential. 2. Manually enter a value into the column for 'percent potential # of activity units for BMP uptake by 2030' 3. For the remaining criteria, enter the qualitative performance and uncertainty scores using the qualitative scales provided in the appendix.	MCF User
6	**Repeat Step (5) for all BMPs being considered in the analysis**	MCF User
7	**Rank by BMPs based on overall score:** Go to Column I, and sort into ascending order	MCF User
8	**Assess outputs and develop next steps based on results:** Go to the 'Results' tab to see graphic outputs of the top 5 BMPs (***Figure 5***)	AFF

A. Overall criteria weighting								B. Uncertainty weighting
			Option 1: Expert ranking of criteria importance.		Option 2: Expert allocation of proportion of criteria importance using value/criteria tree.			Uncertainty weighting relative to performance scores (1=equal weight, 0.5=half weight, etc.) 1.00
Criteria Group	Criteria	ASSIGN CRITERIA WEIGHT [copy criteria weights from Option 1 or Option 2 into this column]	Criteria importance ranking	Criteria weights	Inter-group relative weights	Intra-group relative weights	Criteria weights	Uncertianty weight [Don't edit this column]
GHG BENEFITS	GHG reduction or sequestration potential (to end of time period; to 2030)	0.09	1	0.09	0.33	0.33	0.11	0.09
	GHG reduction or sequestration potential (beyond time period; 2030+)	0.09	1	0.09		0.33	0.11	0.09
	MRV feasibility	0.09	1	0.09		0.33	0.11	0.09
CO-BENEFITS	Soil quality	0.09	1	0.09	0.33	0.25	0.08	0.09
	Water conservation / quality	0.09	1	0.09		0.25	0.08	0.09
	Air quality	0.09	1	0.09		0.25	0.08	0.09
	Biodiversity / pest management	0.09	1	0.09		0.25	0.08	0.09
ADOPTABILITY	Cost of adoption	0.09	1	0.09	0.33	0.25	0.08	0.09
	Financial risks / benefits	0.09	1	0.09		0.25	0.08	0.09
	Adaptation benefits	0.09	1	0.09		0.25	0.08	0.09
	Regulation barriers	0.09	1	0.09		0.25	0.08	0.09
	CHECK total = 1.00	1.00		1.00			1.00	1.00

Figure 2. *Step 1: assign weight to each criterion in the "Weighting" tab.*

Instructions:
1. For each criteria within each BMP, use the scales in the 'Qualitative input' tab to enter a qualitative score using the drop down menu for both the:
    a. Performance score
    b. Uncertainty score
2. Don't enter a score if you feel unqualified to score a BMP for a given criteria (leave it blank)
3. Comments aren't required for every score, but can be added to provide additional reasoning for an assigned score

	GHG long-term benefit						MRV Feasibility		
BMP short	GHG long-term benefit	Benefit Score 1	Comments	GHG long-term benefit uncertainty	Uncertainty score 1	Comments	MRV feasibility	MRV score	Comments
See instructions above	Enter below	DO NOT MODIFY	Enter below	Enter below	DO NOT MODIFY	Enter below	Enter below	DO NOT MODIFY	Enter below
4R nutrient management	Very positive impacts	4		Low uncertainty	3		Somewhat operational	2	
Anaerobic digestion - renewable biogas	Very positive impacts	4		High uncertainty	1		Somewhat operational	2	
Cover crops	Somewhat positive impacts	3		Moderate uncertainty	2		Somewhat operational	2	
Electric tractors	Very positive impacts	4		Moderate uncertainty	2		Very operational	4	
Feed additive - 3NOP	Very positive impacts	4		High uncertainty	1				
Greenhouse retrofit	Very positive impacts	4		Moderate uncertainty	2		Very operational	4	
Manure composting	Very positive impacts	4		Moderate uncertainty	2		Not close to operational	1	
Nitrification inhibitor - DCD	Very positive impacts	4		Low uncertainty	3		Somewhat operational	2	
Plant woody perennials	Somewhat positive impacts	3		Low uncertainty	3		Very operational	4	
Preserve forests	Very positive impacts	4		Low uncertainty	3		Very operational	4	
Rotational grazing	Neutral	2		High uncertainty	1		Somewhat operational	2	

Soil Quality						Water conservation/quality					
Soil quality co-benefit	Benefit score 2	Comments	Soil quality co-benefit uncertainty	Uncertainty score 2	Comments	Water conservation/quality co-benefit	Benefit score 3	Comments	Water conservation/quality co-benefit uncertainty	Uncertainty score 3	Comments
Enter below	DO NOT MODIFY	Enter below	Enter below	DO NOT MODIFY	Enter below	Enter below	DO NOT MODIFY	Enter below	Enter below	DO NOT MODIFY	Enter below
Somewhat positive impacts	3		Moderate uncertainty	2		Very positive impacts	4		Low uncertainty	3	
Neutral	2		Low uncertainty	3		Somewhat positive impacts	3		Moderate uncertainty	2	
Very positive impacts	4		Low uncertainty	3		Very positive impacts	4		Low uncertainty	3	
Neutral	2		Very certain	4		Neutral	2		Very certain	4	
Neutral	2		High uncertainty	1		Neutral	2		High uncertainty	1	
Neutral	2		Very certain	4		Neutral	2		Very certain	4	
Somewhat positive impacts	3		Low uncertainty	3		Somewhat positive impacts	3		Low uncertainty	3	
Neutral	2		Moderate uncertainty	2		Very positive impacts	4		Low uncertainty	3	
Very positive impacts	4		Low uncertainty	3		Very positive impacts	4		Moderate uncertainty	2	
Very positive impacts	4		Very certain	4		Very positive impacts	4		Low uncertainty	3	
Somewhat positive impacts	3		Low uncertainty	3		Somewhat positive impacts	3		Low uncertainty	3	

Figure 3. *Step 3: complete qualitative scoring in the"Qual_input" tab for each user.*

Multi-performance score framework to identify optimal BMPs for GHG benefits in B.C. agriculture Draft V4_April 2021				
BMP Information				
BMP	NIR Category	NIR Sub-category	GHG	Activity Unit
Enter Below	DO NOT MODIFY	DO NOT MODIFY	DO NOT MODIFY	DO NOT MODIFY
All farms - Preserve forest from conversion to cropland	LULUCF	Forest land convert to cropland	CO2e	Hectare
Total - Cover crops	Combined	Combined	CO2e	Hectare

Figure 4. *Step 4: select the BMPs of interest from dropdown menu in the "MCF" tab.*

Summary of Top-5 Ranked BMPs Based on the Multi-criteria Analysis						
					Annual GHGs reduction	Uncertainty
Overall rank	BMP	Total performance score	Total uncertainty score	Overall score	kt CO2e/yr	kt CO2e/yr
1	All farms - Preserve forest from conversion to cropland (50%)	89.30	61.36	150.66	-776.00	-784.68
2	Total - Cover crops (50%)	77.20	68.54	145.74	-141.90	-29.81
3	Total - 4R nutrient management (50%)	72.77	69.14	141.91	-3.00	-0.43
4	Cropland - Plant woody perennial - hedgerows on perimeter of cropland (50%)	61.56	60.26	121.83	-76.43	-90.67
5	Total - Nitrification inhibitor - DCD (50%)	75.60	56.82	132.42	-13.09	-1.58

Figure 5. *Step 8: review summary table and result graphs in the "Results" tab.*

5. Preliminary analyses and results

Using the three criteria weighting scenarios: 1) equal, 2) producer, and 3) public (detailed in **Section *3.5. Criteria weighting in the MCF***), we evaluated how different criteria weightings affect the final BMP scores while keeping all other factors (adoption rates, qualitative scoring, etc.) constant. We also tested two more scenarios to demonstrate more "real-world" applications of the MCF. For 'scenario 4', we again used public stakeholder criteria weighting, but we reduced the weighting of all uncertainty scores to zero (0). Scenarios 1-4 were performed with an adoption rate of 50% across all BMPs (i.e., the BMP is applied to 50% of all potential activity units, however, for 'scenario 5', we used hypothetical, and varied, adoption rates across the BMPs (see **Table 7**). In 'scenario 5' we also excluded any GHG benefits that would technically be recorded in the LULUCF "memo items" in the provincial inventory (for cropland and grassland management), and therefore not counted towards the total. In 'scenario 5' we used the public stakeholder criteria weighting as used in 'scenario 3' and 'scenario 4'. These scenarios are summarized in the first three rows of **Table 8**.

***Table** 7. Theoretical adoption rates (%) for BMPs in 'scenario 5'.*

BMP	Theoretical adoption rate (%)
4R nutrient management (annual crops)	40
Anaerobic digestion: renewable biogas	10
Best-in-class greenhouse retrofit	15
Cattle feed additive: 3NOP	40
Cover crops *	25
Manure composting	15
Nitrification inhibitor: DCD	10
Plant woody perennials **	0
Preserve forest from conversion to cropland	10
Replace diesel tractors with electric	15
Rotational grazing (basic) ***	10
Rotational grazing (intensive) ***	10
For 'scenario 4', we only included GHG benefits that could be counted in the Provincial Inventory (i.e., excluding C sequestration reported in the LULUCF memo-items for cropland and grassland management). Therefore, the following adjustments to BMPs were made:	

* Cover crops: only direct N_2O emission reductions are included; C sequestration is excluded from the 'scenario 4' analysis.

** Plant woody perennials: C sequestration in cropland is excluded, therefore this BMP is entirely excluded from the 'scenario 4' analysis.

*** Rotational grazing: only enteric fermentation emission (CH_4) reductions are counted; C sequestration is excluded from the 'scenario 4' analysis.

We used the same qualitative scoring across all scenarios, which we collected from six different "users". This included each of the five members of our team, plus we entered data for a "user 6", which represents any input we gathered from AFF agrologists regarding qualitative scoring. Qualitative scores were averaged across the six "users" before being entered into the MCF tool. A summary of the results of these 'scenario' analyses are provided in **Table 8**.

The BMP 'cover crops' ranked first across all scenarios (**Table 8**) with one exception: in scenario (4), when uncertainty scores were weighted to zero, 'cover crops' ranked third to 'preserve forests' and 'greenhouse retrofit', which reflects an increased ranking for these two BMPs when uncertainty is less important in decision making. The 'preserve forests' BMP also ranked in the top five in the other four scenarios. Overall, the 'cover crop' and 'preserve forests' BMPs have relatively large potential for GHG benefits and are also likely to provide important environmental co-benefits. In contrast, the 'greenhouse retrofit' ranked top five in all the scenarios except for scenario (2) with industry criteria weighting; given the upfront costs and relatively few co-benefits to producers of the 'greenhouse retrofit' BMP, this BMP was not ranked as highly in this scenario. In contrast, the BMP 'nitrification inhibitor – DCD', ranked fifth only in this scenario using industry criteria weighting (scenario (2)).

The BMP '4R nutrient management' also ranked in the top five in all scenarios except (4), where uncertainty was not considered. In this scenario, the BMP '4R nutrient management' was outranked by more "high reward" but potentially "high risk" BMPs, like 'anaerobic digestion'. The BMP 'anaerobic digestion' ranked fifth in this scenario (scenario (4)), but was not top five in any of the other scenarios. The BMP 'plant woody perennials' was the next most highly ranked in the scenarios it was included in (ranked second, third or fourth in scenarios 1 – 4). This reflects the potential for this BMP to satisfy a variety of stakeholder values or priorities, with both GHG benefits and environmental co-benefits.

The BMP 'feed additive – 3NOP' only ranked in the top five when public stakeholder weightings were used and theoretical adoption rates were applied (scenario (5)). Given that

3NOP is not currently permitted for use in Canada, and therefore received a zero qualitative score for the "regulatory barriers" criteria, it did not rank highly in either the equal weighting scheme or the industry stakeholder weighting scheme. In addition, for scenario (5), the 3NOP BMP was assigned a relatively high (40%) hypothetical adoption rate, which increases the potential for GHG benefits by being applied to a greater number of activity units. These outcomes illustrate how shifting the MCF tool in scenario (5) to de-emphasize regulatory barriers (i.e., the regulatory barriers criteria is set to zero in the public stakeholder weighting scheme), and implement variable levels of adoption, can highlight promising BMPs that are not yet permitted (or highly regulated) but worth consideration if uptake could be relatively high once they are permitted for use.

It is important to note that scenarios 1-3 simply reflect differences in how the criteria weightings can be changed (and in scenario (5) – how uncertainty weighting can be changed). Of the five scenarios, 'scenario 4' provides a preliminary illustration of how outcomes can change when input variables are refined more specifically. However, these initial analyses do not reflect how rankings would change if different qualitative scoring were used, i.e., if new data were incorporated into the assessment based on new research or if subject matter experts were consulted more exhaustively.

Table 8. *Comparison of top five BMPs across four different criteria weighting scenarios showing their score and associated ranking. Shading indicates which emissions sector the BMP could technically be accounted in, where gold = 'LULUCF', green = 'Agriculture', and blue = 'Energy'.*

	Scenario 1: Equal weights		**Scenario 2: Industry stakeholder**		**Scenario 3: Public stakeholder**		**Scenario 4: Public stakeholder**		**Scenario 5: Public stakeholder ***	
	50% adoption								*Theoretical adoption rates; see* **Table 7**.	
	Uncertainty weighting = 1						*Uncertainty weighting = 0*		*Uncertainty weighting = 1*	
1	Cover crops **	150	Cover crops **	156	Cover crops **	133	Preserve forests	87	† 4R nutrient management / Cover crops	128
2	Preserve forests	144	4R nutrient management	146	4R nutrient management	128	Greenhouse retrofit	79	Greenhouse retrofit	126
3	Plant woody perennials	141	Plant woody perennials	142	Greenhouse retrofit	127	Cover crops	78	Feed additive – 3NOP	123
4	4R nutrient management	139	Preserve forests	138	Plant woody perennials	125	Plant woody perennials	77	Preserve forests	121

5	Greenhouse retrofit	121	Nitrification inhibitor – DCD	134	Preserve forests	124	Anaerobic digestion	75	Nitrification inhibitor – DCD	115

* 'Scenario 5' only assessed BMPs for the GHG benefits that are counted within subcategories that are currently counted in the PI; see notes in **Table 7**.
** Cover crops provide GHG benefits primarily through increased C in soil, which is counted in the LULUCF sector, but can also reduce N_2O emissions from soils, which is counted in the 'Agriculture' sector. Rotational grazing also provides GHG benefits primarily through increased soil C (LULUCF), but also reduces enteric fermentation emissions (counted in 'Agriculture').
† These BMPs have the same score

The annual GHG benefit potential and comparison of benefit vs. uncertainty scores for the top five BMPs are illustrated in **Figure 6**. Although the 'preserve forest from conversion to cropland' BMP ranks highly across most criteria, the uncertainty associated with its GHG benefit potential is substantial. Uncertainty for the activity data was assumed to be 100% given the limited data available for deforestation rates on agricultural land. In contrast, 'cover crops' has a similar projected GHG benefit potential, but with lower uncertainty. The trade-offs between the three criteria groups for scenario 1 (equal weights) are illustrated in **Figure 7**.

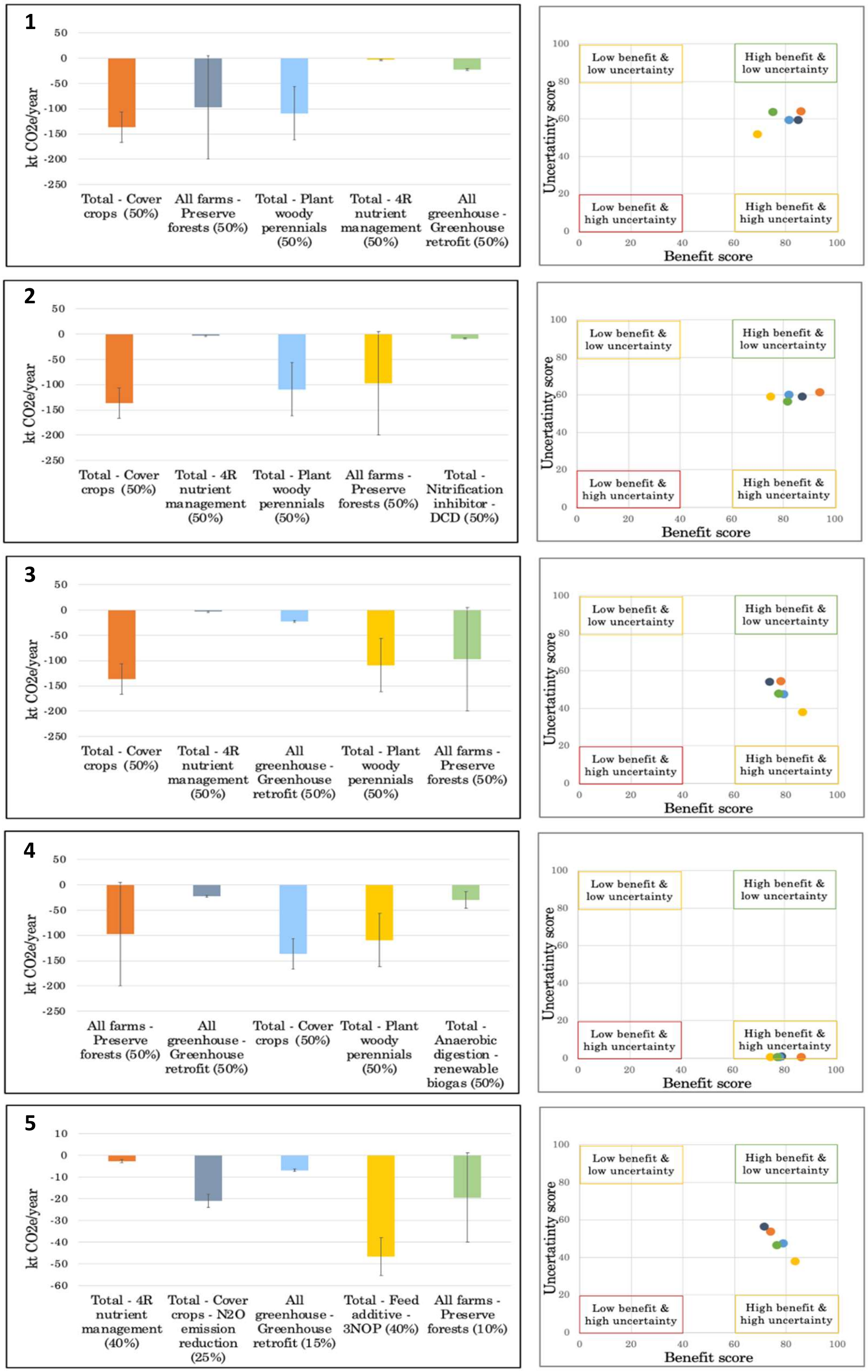

Figure 6. *Annual GHG reduction potential and total benefit and uncertainty scores for the top five BMPs identified in the MCF for hypothetical scenarios – 1) equal weighting, 2) producer stakeholders, 3) public stakeholders, 4) public stakeholder weighting with variable adoption rates, and 5) public stakeholders with uncertainty weighted to zero.*

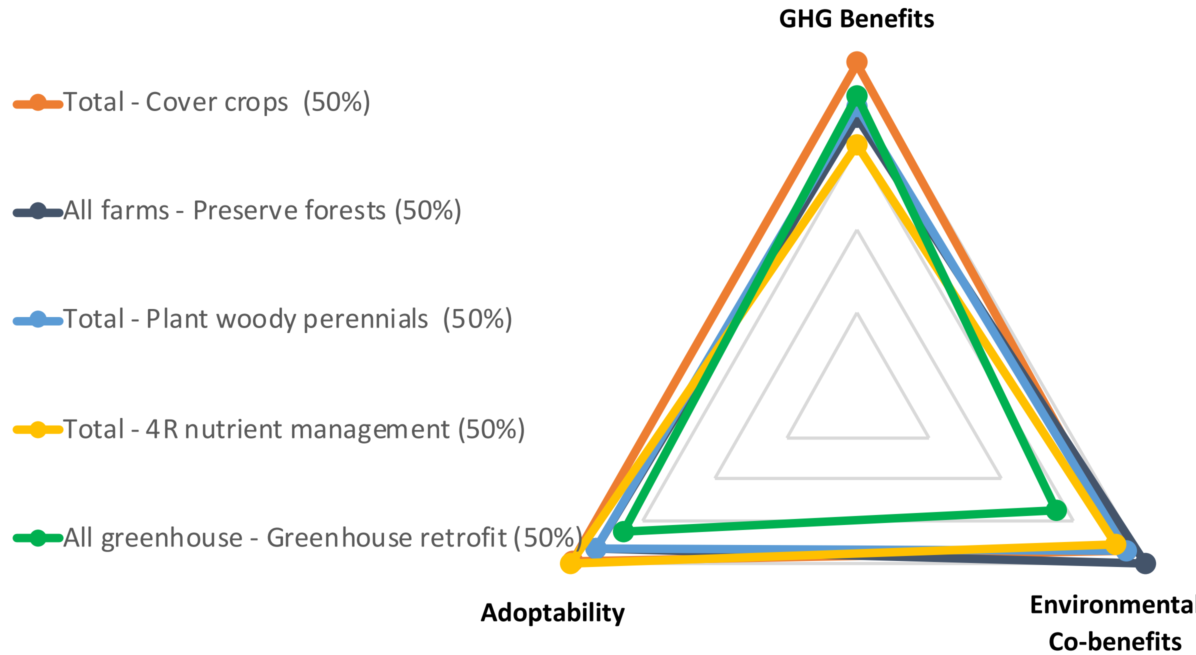

Figure 7. *Example output illustrating trade-offs among the three criteria groups for 'scenario 1': equal weighting with 50% adoption. The further outside a data point is in the triangle the higher a BMP scored in that criteria group; colour indicates BMP.*

5.1. GHG emission benefits of preliminary BMPs

An important outcome of developing a robust BMP database is the capacity to evaluate BMPs for their relative potential GHG benefits as well as their combined potential contribution to meeting provincial targets. The BC *Climate Change Accountability Act* requires that BC's GHG emissions must be reduced by 40, 60, and 80% below 2007 levels by 2030, 2040, and 2050, respectively. Emission reduction targets for individual sectors were set by the BC Minister of Environment and Climate Change in March 2021. These targets are expressed as a range of five percentage points and apply to four BC sectors. Legislated reduction targets have been set at 27 to 32% for transportation, 38 to 43% for industry, 33 to 38% for oil and gas, and 59 to 64% for buildings and communities sectors (ECCS 2021). Agricultural emissions are categorized under several of these sectors (Ken Porter, personal communication, June 3, 2021) and could contribute to meeting their emission reductions targets. Agricultural emissions are categorized as follows: On-farm transportation emissions are in the transportation sector; On-farm stationary combustion and crop and livestock production are in the industry sector; and

Emission from deforestation (forestland converted to cropland) are in the Buildings and Communities sector[4]. Emissions from cropland management related to storage and release of CO_2 from soil organic matter and woody biomass are not counted in the provincial inventory (reported as memo items), and therefore would not currently be associated with emission reduction targets. There is increasing evidence that natural climate solutions, particularly BMPs that sequester C in agricultural soils could contribute substantially to emission reduction targets globally (Griscom et al. 2017) in Canada (Drever et al. 2021). There are several jurisdictions around the world that are currently moving forward with the development of BMPs and accounting strategies that could enable the incorporation of agricultural soils C sinks into emissions target contributions e.g. California's Healthy Soil Initiative. Our results indicate that this could be an important opportunity for BC as well.

Given the coarse level of our analysis, we have simply assessed the potential for these preliminary set of BMPs to contribute to the general 40% reduction target by 2030. Provincial emission reduction targets in BC are based on 2007 emission levels; emissions from the Agriculture sector in BC in 2007 were 2,465 kt CO_2e $year^{-1}$ (as reported in the 2020 NI and Provincial Inventory (PI)); thus, leading to an emission level target of 1,479 kt CO_2e $year^{-1}$. To meet this emission target, emissions need to be 994 kt CO_2e $year^{-1}$ below current (2018) emission levels which were 2,473 kt CO_2e $year^{-1}$. However, the Agriculture sector, following the IPCC definition and used in the NI and PI, does not account for emissions from on-farm fuel use (Energy) or carbon sequestration (LULUCF (See our *Report 1: BC Agriculture GHG Emission Profile Analysis* for further details on emissions accounting). When accounting for agricultural emissions from Agriculture, on-farm fuel use (Industrial Products and Processes and Solvent Use, and Energy), and LULUCF, 2007 emissions were 3,242 kt CO_2e $year^{-1}$. Based on these emissions, a 40% reduction would require an emission level target of 1,945 kt CO_2e $year^{-1}$. Compared to 2018 levels across these three sectors (3,794 kt CO_2e $year^{-1}$), a reduction of 1,849 kt CO_2e $year^{-1}$ in agricultural emissions is needed to meet this comprehensive 2030 target. **Figure 8** shows a summary of the BMP benefit potential for the BMPs included in this analysis

[4] For details on the distribution of emission see *Report 1: BC Agriculture GHG Emission Profile Analysis*

at three different adoption rates (10, 25, and 50%). The top four BMPs are associated with GHG benefits from C storage in soils and woody biomass (i.e. natural climate solutions), which are accounted for in the LULUCF inventory sector. Importantly, while emissions from land conversions (afforestation and deforestation) are counted towards the provincial total, all other LULUCF line items (i.e. 'land remaining' / unconverted lands) are reported as memo items in the BC PI and not counted in the provincial total.

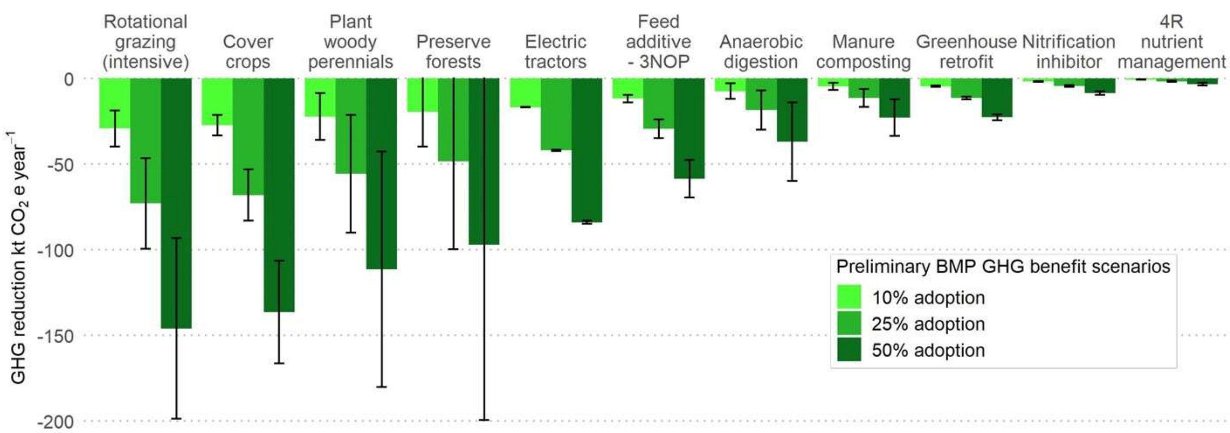

Figure 8. *Annual GHG benefit potential by BMP under three levels of adoption (10, 25, and 50%).*

Figure 9 shows the emission reduction when the preliminary set of BMPs are combined and estimated for three adoption levels achieved by 2030 relative to emissions in 2018. This combined emission reduction potential is illustrated compared to a reduction target of 40% below 2007 levels. We estimate that reaching a 50% adoption level for all the BMPs included in this analysis would result in an annual GHG benefit of -718 (± 132) kt CO_2e year^{-1}, which is only a 5% reduction in emissions relative to 2007. In comparison, with a more achievable adoption level of 25%, GHG benefits are estimated as -359 (± 66) kt CO_2e year^{-1}which would nearly offset the increase in emissions since 2007. All of the adoption scenarios and potential GHG benefits were calculated under the assumptions that the target adoption rate is met by 2030 and there is no emission increase from other sources of Agriculture, Energy, and LULUCF during this period. Our estimates are comparable to those of the recent national level analysis of natural climate solutions by Drever et al (2021) that indicate BC agriculture could provide 310 kt CO_2e of GHG benefits at a similar adoption level (24% by 2030). Given our estimates do not include several BMPs that they identified yet include benefits from non-natural climate solutions such as electrifying tractors there should be further analysis to rectify the differences in these emission reduction estimates. Drevel et al (2021) include, for example, additional BMPs related to tree planting (intercropping and silvopasture), the use of biochar and the restoration of wetlands that could provide sizable additional emission reductions for BC. Our estimate therefor should be seen as a first step towards establishing the overall potential for agricultural BMP to contribute to emission reduction targets in BC.

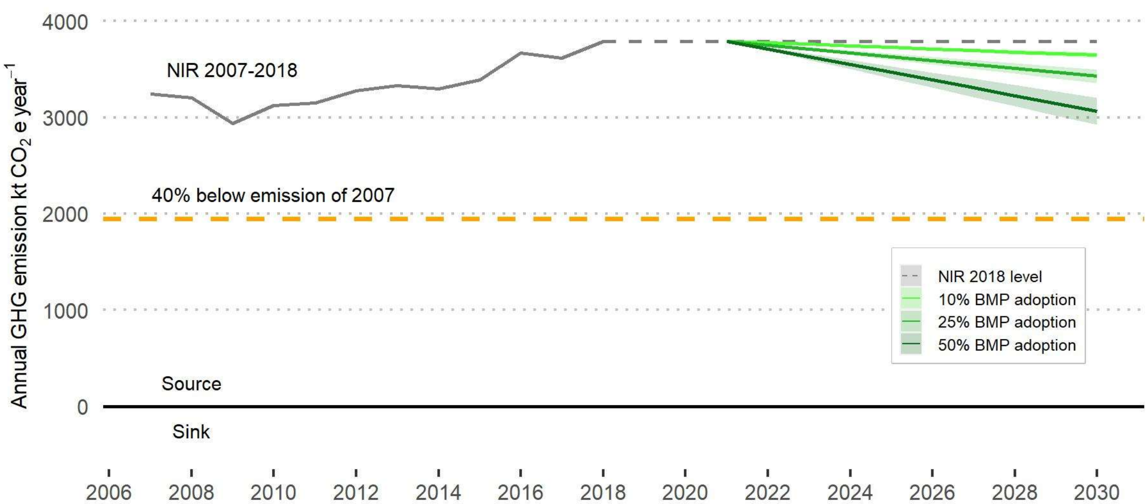

Figure 9. *Emission reduction potential of the preliminary set of Beneficial Management Practices by combined projected emission reductions based on three adoption levels achieved by 2030 relative to emissions in 2018. Shaded areas indicate uncertainty in GHG benefit potentials.*

5.2. BMP Limitations

Given that the development of BMPs was not the primary focus of the project, and our time dedicated to this was limited, the list of BMPs, and their estimated GHG benefits should be seen as very preliminary. The BMPs selected for this preliminary analysis is not an exhaustive list of potential options, and additional BMPs need to be identified and researched for their GHG benefits and environmental co-benefits.

For many BMPs we lacked appropriate data, we often used important assumptions, and in general applied a fairly simplistic approach to our calculations which together limit the accuracy of our BMP GHG benefit estimates. Some of these assumptions are related to lack of provincially specific activity data, and others to the emission reduction factors. In some cases, our combined uncertainties were more than 100%. The data that was most difficult to determine was the overall potential activity units to which the BMP could be applied in the province. This limitation is related to the lack of a spatial approach to our analysis. For example, while there have been some studies in the lower Fraser Valley that have estimated the potential for additional farm edge or riparian buffers, we did not find any outside of this region. In cases like these we relied on input for AFF agrologists and tried to be as conservative as possible (i.e. we erred to the side of low GHG benefits). For most of the BMPs we did not account for the large variation in soils or climate that inevitably will impact the GHG benefit outcomes. For only a few were we able to include a simplistic approach to account for soils or climate. Finally, although the performance of many of these BMPs is predicated on complex ecological interactions that make for dynamic performance over time, we have again taken a very simplistic approach where the performance is strictly time averaged between an assumed deployment year of 2022 and the year of the emission target, 2030. We know that many of the BMP GHG benefits will vary over time but a more complex approach was beyond the scope of our analysis. For cases where we had clear data that the GHG benefits were likely to change in the long-term we have taken a qualitative approach to indicate this in the MCF tool as a yes/no criteria for all years beyond 2030. More details of these limitations for each BMP and their assumptions and uncertainties are provided in the BMP synopsis found in the appendix. Here we provide a couple of clear examples of areas where the BMP analysis could be improved.

Further research into additional or alternative BMPs for enteric fermentation emissions could have important implications for BC agriculture to contribute to emissions targets given the size of this emissions source. We included one feed additive, 3-nitrooxypropanol (3NOP), but there are many other feed additives that can be considered, i.e., seaweed, fatty acids, nitrate, biochar (Honan et al. 2021). We included 3NOP based on broad availability of peer-reviewed literature demonstrating consistent and meaningful reductions in CH_4 emissions (with relatively low levels of associated uncertainty) with this additive (e.g., Honan et al. 2021). However, future work should engage local researchers who have active projects evaluating feed additives (e.g., Thompson Rivers University). Some feed additives would likely require life cycle assessments to developed effective estimates of GHG benefits given the potential for increasing indirect emissions through processing and transport (i.e., seaweed).

Another important area of improvement would be the identification and development of BMPs that are specifically appropriate for individual commodities or commodity groups given that they may be responsible for BMP development and promotion. This was not the focus when we identified our preliminary list of BMPs and our estimates of GHG benefits, costs and co-benefits are often applied homogenously across commodities. Our approach for developing BMPs for perennial production (e.g., berries, tree fruit, nuts) is an important example of this limitation. While, the emissions profile of this sector is relatively small, it is economically important for the province and an area of growth. For our analysis we have only identified the BMP, '4R nutrient management,' for perennial production but our method for estimating the emission reductions is currently based on data developed for annual production. Other BMPs have been studied specifically for perennial systems in BC such as bark mulch in fruit tree orchards to reduce N_2O emissions from soil but were not included in our preliminary list. Researchers at UBC Okanagan found bark mulch reduced N_2O emissions in both grape vineyards and apple orchards in the Okanagan (Fentabil et al. 2016b, 2016a); however, based on their lifecycle assessment of mulch use in apple orchards, they do not recommend this as a GHG mitigation strategy due to an increase in indirect GHG emissions associated with the production and application of the mulch (Bamber et al. 2020). However, these researchers point out that there may be an alternative way to produce and use bark mulch in these orchards that do not increase indirect emissions, and this research will tentatively be released in future publications (Bamber et al. 2020). Another BMP option to consider in future analyses is increased drainage in berry production fields in the lower Fraser Valley; our lab is currently conducting research in this area (assessing impact of drainage types on GHG emissions from blueberry fields in Delta), and future results can inform BMP development in this area.

Additional BMPs for future consideration for BC agriculture, suggested by AFF agrologists during a feedback period in May 2021include: planting perennial/permanent forage, use of permaculture, integration of aquaculture and land-based agriculture, conservation/reduced tillage (i.e., with roller crimpers for cover crops), and management that improves silage storage, feed-out, and reduced silage dry matter loss from spoilage on livestock (primarily dairy) farms. There are many other farm management practices, efficiencies, and technologies, that could be considered as BMPs for GHG benefits for the BC agricultural sector, that can be found in Hall

(2017), Powell (2018), or Dobbs (2014) as well as those compiled in our BMP Literature Database.

5.3. Current Provincial BMP programming

The Beneficial Management Practices Program, administered through the Environmental Farm Plan (EFP) Program is the primary mechanism for BC producers to receive cost-shared funding incentives to implement projects that reduce farms' environmental impact (Government of British Columbia n.d., British Columbia Agriculture Research and Development Corporation 2020). The BMP's that we have included in this assessment are listed in **Table 9** with their corresponding practices eligible for cost-shared funding through the EFP BMP program, if applicable.

The Canada – BC Agri-Innovation Program also provides funding for practices / activities related to research, development, demonstration, and commercialization and adoption of 'new-to-B.C.' products or technologies (Investment Agriculture Foundation n.d.). Not all BMPs would be eligible under this program, but more 'innovative' practices such as electric tractors or feed additives such as 3NOP could be candidates for funding and development. The Delta Farmland and Wildlife Trust provides funding to farmers in the Fraser River Delta to plant winter cover crops and implement grassland set-asides (Delta Wildlife and Farmland Trust 2021). To a lesser degree, they also provide support for through a cost-share for land taken out of agricultural production to establish new hedgerows. The BC Cattlemen's Association manages and delivers the Farmland-Riparian Interface Stewardship Program (BC Cattlemen's Association 2021). This program provides support to cattle ranchers to improve riparian areas by providing technical information or budget estimates, identifying funding sources, and mediating landowner conflict, but does not directly providing funding for riparian restoration projects. Farmland Advantage has also provided substantial support for ranchers to improve riparian areas and is now in the process of expanding operations across the province. Fortis BC provides rebate incentives to upgrade to efficient natural gas boilers (Fortis BC 2021).

Table 9. *Summary of practices eligible for cost-shared funding in the 2020/21 British Columbia Beneficial Management Practice program.*

BMP included in this analysis	Applicable EFP BMP Program Support 2020/21

4R nutrient management (annual crops)	• *Nutrient management planning, basic:* 100% cost share to $3k, *complex:* $3k plus 50% cost share to $6k cap • *Low disturbance placement of seed and fertilizer:* 30% cost share – $30k cap • *Precision guidance applications (GPS):* 30% cost share – $10k cap • *Specific equipment for land applications of agricultural by-products (manure)*: 30% cost share – $20k cap • *Specific equipment for applications of fertilizer*: 30% cost share – $20k cap • Improved land application of agricultural by-products: 30% cost share – $20k cap
Anaerobic digestion	• *Covered manure storage in combination with methane collection and renewable energy production from collected methane:* 30% cost share – $30k cap – requires nutrient management plan; dairy or hog producers only
Best-in-class greenhouse retrofit	• *Energy assessments completed by a qualified professional:* 100% to $3k, 80% to $10k • *Engineering or technical design work or technical feasibility studies (methane reduction):* 50% cost sharing – $20k • *Replacement of fossil fuel dependent space heating with renewable energy source:* 30% cost share – $30k cap • *Thermal energy efficiency improvements:* 30% cost share – $30k cap • *Lighting efficiency improvements:* 30% cost share – $10k cap • *Energy monitoring and controls:* 30% cost share – $30k cap • *Power line extension:* 30% cost share – $30k cap
Cattle feed additive: 3NOP	• *Feed additives to ruminant feed that has a proven effect of reducing enteric fermentation trial:* 30% cost share – $5k cap – maximum one year funding to trial; does not explicitly list 3NOP as eligible (lists proteins, seaweeds, dietary fats)
Cover crops	• None*
Manure composting	• *Engineering or technical design work by a qualified professional (organic residuals – composting):* 100% to $3k plus 80% to $10k cap • *Composting of agricultural waste:* 30% cost sharing – $25k cap
Nitrification inhibitor: DCD	• None*
Plant woody perennials	• *Riparian management planning:* 100% cost share – $1k cap • *Vegetative buffer planning:* 100% cost share – $2k cap • *Establishment of vegetative shelterbelts, buffers, or hedgerows:* 60% cost share – $15k cap • *Riparian habitat establishment:* 60% cost share – $30k cap

	• *Fencing to manage grazing and improve riparian condition and function:* 60% cost share – $30k cap • *Erosion control and riparian habitat structures:* 60% cost share – $30k cap
Preserve forests from conversion to cropland	• None*
Replace diesel tractors with electric	• *Replacement of fossil fuel driven engines with electric motors:* 30% cost share – $10k cap • *Power line extension:* 30% cost share – $30k cap • *Alternative energy technology:* 30% cost share – $30k cap
Rotational grazing (basic or intensive)	• *Grazing management planning:* 100% cost share – $1k cap • *Fencing to manage grazing and improve riparian condition and function*: 60% cost share – $30k cap; repairing existing fencing not eligible • *Native range and restoration or establishment:* 60% cost share – $30k cap • *Grazing management in surrounding uplands:* 60% cost share – $30k cap • *Improved grazing systems – cross fencing to create biodiversity enhancements:* 60% cost share – $30k cap • *Alternative watering systems to manage livestock*: 60% cost share – $30k cap • [other BMPs can also help facilitate changes required for the adoption of rotational grazing, such as relocation of facilitates, improved stream crossings, etc.]

**Creative environmental solutions:* 30% cost share – $30k cap

6. Recommendations

Effective implementation of the MCF largely depends on the quality of data and use of criteria chosen for the MCF. In terms of MCF criteria, it matters how criteria are 1) selected given project objectives, 2) scored for the individual BMPs based on (or constrained by) the data and information available, and 3) weighted based on expert ranking and valuation of criteria importance. Notably, regarding (2), it is expected the main limitation will be gaps in data or BMP information specific to agricultural activity in BC. Thus, expert review of the performance matrix should also reveal where future data/information compilation efforts are most needed. For example, an in-depth review of the summary of qualitative scoring used in the MCF (compiled in the 'Qual_data_summary' tab in the MCF excel) can be used to identify which BMPs are consistently associated with high levels of uncertainty.

6.1. Expert and stakeholder involvement

Expert and stakeholder involvement are needed for selection and weighting of criteria, and selection of outcomes (Sánchez et al. 2016). In **Figure 10**, we illustrate the iterative process of how expert decisions can occur at different stages and be integrated with other modelling tools. First, to score performance of each BMP for qualitative criteria, collaborative data collection methods can be used to collate expert opinion. We provide an example of a scoring table to demonstrate how this approach can be integrated into the MCF ("Qualitative Data – Prototype" in the MCF Excel tool. Briefly, this type of scoring table would combine qualitative performance and uncertainty scores from different users for a variety of BMPs (listed in the first column) among the qualitative criteria (i.e. environmental co-benefits and adoptability). These would be using the qualitative scoring scales of 0-4, as described in the Appendix. Then, scores would be averaged across users, and score variability can be checked to ensure some consistency amongst users (i.e., using a co-efficient of variation).

Increased engagement can also be used to determine the weighting of criteria among target stakeholders (i.e., AFF, producers, researchers), focus groups, workshops, and/or questionnaires can be used to collate weightings and average weights can be applied to the analysis. Alternatively, stakeholders can validate that weightings used by experts are in line with their perception of relative importance. Expert review of MCF output is recommended to ensure scoring and weighting are appropriate. This can include checking if the MCF is overly sensitive to adjustments in certain criteria or weightings over others, and if the MCF results are acceptable and in line with decision-making objectives. Experts should also be utilized to determine the adoption potential (% of total activity units) as it has substantial influence on the GHG benefit potential of the each of the BMPs. While our analysis has thus far focused on uniformly changing the adoption potential (i.e., 10%, 25%, and 50% adoption) this does not reflect the reality that some BMPs could be adopted to greater extents than others. Nor does it reflect that the adoption rate may be variable over time. Therefore, expert judgement by specialists familiar with the BMP, the applicable industry, current rate of adoption and producer perception of the BMP is required. More accurate estimates of the potential adoption of each of the BMPs will enable more realistic comparisons across BMPs. At the same time, more accurate adoption potential can provide improved insight of GHG benefit potential and planning of BMP prioritization and targets for adoption that will meet provincial emissions targets.

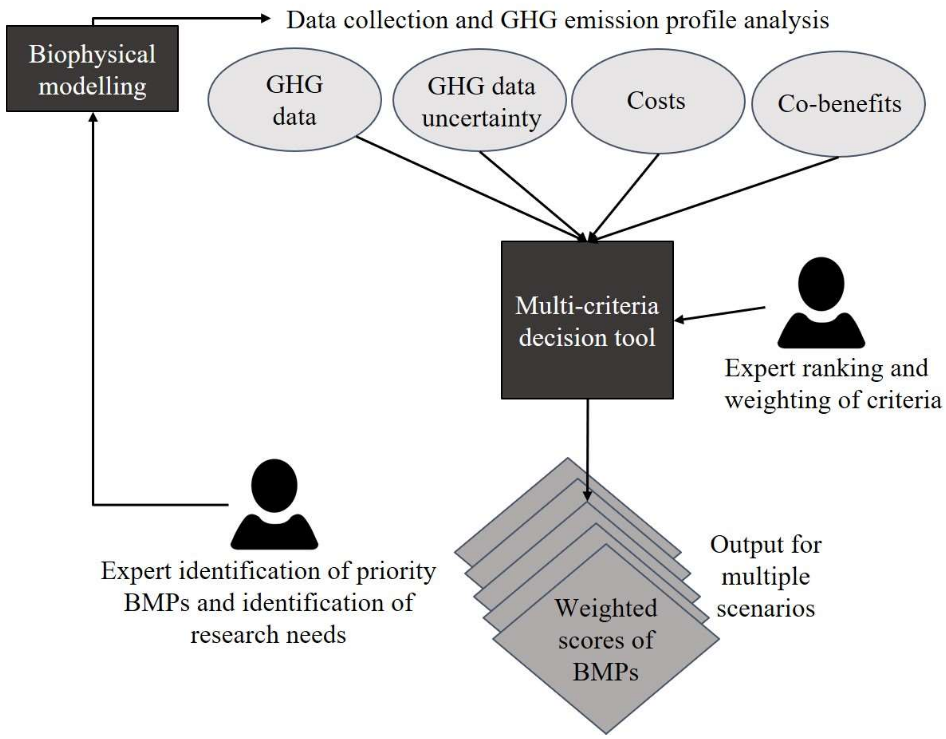

Figure 10. *Overview of multi-criteria framework process highlighting the contributions of experts and the iterative development of outcomes.*

Input from various stakeholders and experts, a series of scenarios can then be compared to better understand the potential of BMPs. These scenarios can be developed, as we have done, at aggregated levels of the BMPs for a broad assessment of the BMP potential a provincial level or they could be applied for particular sub-categories or regions to develop regional or commodity driven approaches. Given the lack of data for many BMPs, this process could be an important tool for identifying research priorities by illustrating BMPs with large GHG benefit potential, and co-benefits but large uncertainties.

Finally, the MCF process could be enhanced enormously if integrated with biophysical models that could provide improved spatially explicit and more accurate temporal estimates of GHG benefit. As it is now, estimates of regional BMP performance include only an extremely limited integration of variation in climate and soils in the province, and BMP performance over time has been simplified into only short- or long-term (before or after 2030). How these limitations impact the overall ranking of BMPs would depend on how important uncertainty is in the process. Given the complexity of modeling BC's diverse agriculture, soils and climate, the benefits of this effort should be considered carefully. We provide a detailed assessment of modeling options for BC in our *Report 3: Agroecosystem Models for GHG Emissions and Co-Benefits*.

6.2. BMP database development

The BMP database, to date, is far from the exhaustive database required for this type of robust MCF analysis. A more thorough literature review will improve the analysis of BMPs most likely to provide the most effective GHG benefits and co-benefits for agriculture in BC and it is likely that additional empirical or modeled data will be required. While the BMPs that have been included in the database are the most developed in terms of available peer reviewed studies, work is required to develop robust estimates for BC's highly diverse agricultural systems. Our analysis has identified BMPs such as planting and conserving trees and shrubs on agricultural land that have great potential GHG benefits but have very large uncertainties associated with both their emission reduction factors and activity data. Priority should be placed on reducing the uncertainty on these "high-risk but high-return" BMPs. In addition, our current work in BMP data collection was largely focused on gathering quantitative GHG benefit and adoption cost data; scores for environmental co-benefits and adoptability rely on expert judgement or consultation from AFF and/or industry, or will require further research.

6.3. Incorporate temporal and spatial components into the analysis

Another important next step would be to incorporate an approach that better reflects the temporal and spatial-explicit performance of the BMPs in calculations of emissions benefits and aggregated reporting. Many of the BMPs that are appropriate for BC agriculture vary in their performance over time, by soil type and by climate. Incorporating these components into BMP benefit calculations will help to reduce uncertainties and enable a more realistic assessment of BMP options. Enabling BMP benefits to be aggregated geographically would enable a comparison of BMP performance within a region to determine which BMPs are best suited for local conditions and commodities. Alternatively, spatially explicit data could be used to prioritize regions across the province for BMP investment. A regional approach would lead to more accurate GHG benefit estimates. Incorporating spatially explicit data could be done simply by expanding the BMP database using activity data from Statistics Canada and climate- and soil-specific emission factors by eco-region and allocating these by region in the BMP database. Queries of the database could then be made by region in the MCF Excel tool. This approach could be enhanced enormously by integrating the MCF with a geographical information service and made online. Further refinement to address both temporal and spatial variability would could include the integration of more complex empirical or more likely, process models. This however would limit future alterations to the MCF to more expert programmers and modelers. There could be important synergies with national BMP development and accounting efforts and we recommend further collaboration and integration with groups like FCS for developing a more robust BMP database and the appropriate cyber infrastructure to house it.

6.4. Developing a measurement, reporting and verification approach

For agriculture to contribute meaningfully to provincial emissions targets by 2030, incentive programming supporting climate BMPs will have to be rolled out widely as soon as possible. It is imperative that as this programming is developed it includes a robust measurement, reporting and verification (MRV) approach (e.g., Government of Alberta 2012, 2015). Given our lack of empirical data on BMP performance specific to BC, an MRV approach is required to ensure that anticipated GHG benefits are actually being achieved and can be credited for emission targets. This is particularly important for BMPs with large uncertainties (e.g. Preserving Forests) or BMPs that provide C sinks (e.g. Rotation Grazing). Data also needs to be collected to better quantify BMP co-benefits. Data collection on the performance of BMPs will in turn enable the development of an adaptive management approach for BMP programming. As more local empirical data is made available, BMPs can be re-assessed and re-prioritized using the MCF. The MRV approach would also support enhancing climate reporting that is required under the *Climate Change Accountability Act* (*Climate Change Accountability Act* 2007) and AAFC's Federal Provincial and Territorial (FPT) reporting on the implementation of the Pan-Canadian Framework on Clean Growth and Climate Change. The development of an MVR approach is needed to track the agriculture sector's efforts to reduce GHG emissions in relationship to the PI and BC's progress to reduction targets. An MRV approach should be developed through collaboration among representatives from industry, government, and provincial scientists to ensure data is collected with the accuracy, precision, resolution, and costs that will effectively address MRV objectives. Developing an effective MRV approach within a timeframe to meet 2030 emission targets will require large amounts of resources that will need to be mobilized immediately.

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Appendix A – BMP synopses

For each of the BMPs included in our preliminary analysis we provide a brief description of the calculations we use to estimate their GHG benefits and associated error, and cost of adoption. We provided AFF agrologists a draft of these BMP synopses and solicited their feedback. For each of the BMPs we include this feedback to be used in the continued development of these BMPs.

GHG benefit potential calculations: Overview

The general approach to quantifying GHG benefits is provided in the report above (**Section 3.4.2. Quantitative scoring in the MCF**). The GHG benefit potential calculated in the MCF Excel tool is determined from a combination of the maximum GHG benefit potential and an anticipated BMP adoption rate. The maximum GHG benefit potential is calculated using three parameters:

Equation 0-1:

$$\boldsymbol{max. GHG\ benefit\ potential = reduction\ factor \times total\ activity\ units \times biophysical\ limit}$$

Where the 'maximum GHG benefit potential' is defined as the maximum quantity of CO_2 sequestered in woody biomass or soil, and/or the quantity of GHG emissions (carbon dioxide - CO_2, methane - CH_4 and/or nitrous oxide - N_2O) reduction that are achievable by implementing a BMP. The reduction factor (RF) is the difference in CO_2 equivalent (CO_2e) emissions between the BMP relative to a 'business as usual' baseline. The total available activity units are the activity units that are recorded in or estimated for the province. The biophysical limit describes any constraints on the quantity of those activity units that the BMP could be applied to, based on biophysical criteria such as climate, soils, or current levels of BMP use. The BMP synopses below describe the data sources and calculations used for determining these three parameters for each BMP.

The final step for determining the GHG benefit potential from a given BMP is then calculated in the MCF as:

Equation 0-2:

$$\boldsymbol{GHG\ benefit\ potential = max.GHG\ benefit\ potential \times adoption\ potential}$$

Where the adoption potential is determined by the MCF tool user as a percentage of how many activity units could be expected to have the BMP applied to, given the total activity units constrained by the biophysical limit.

BMP GHG benefit uncertainty calculation overview

The uncertainty associated with the BMP GHG benefit potential is calculated through error propagation of uncertainty. The uncertainty values we have used are either a variance reported in the literature for the RF, activity, and biophysical limit data (standard deviation or standard error), or we calculated and used a coefficient of variation (% CV) when a range of mean values were provided. Calculating a coefficient of variation, and rules for error propagation are discussed in the following subsections.

Error propagation for combining uncertainties

When quantities are combined through calculations (i.e., addition, multiplication, etc.), we combined the associated uncertainties following the error propagation methods described by Taylor (1997), which are also used in IPCC Guidelines National GHG inventories (Intergovernmental Panel on Climate Change 2006, 2019). In all of the following equations, 'Uncertainty' is entered as relative (percentage) uncertainty.

Based on these references, we have used the following three rules of error propagation:

1. Independent and random errors (i.e., from different data sources), combine through addition in quadrature (Equation 0-3a or modified Equation 1-3b), and nonrandom errors (i.e., from the same study), combine through simple addition (Equation 0-4).

Equation 0-3a

$$Combined\ uncertainty = \sqrt{(Uncertainty\ 1)^2 + (Uncertainty\ 2)^2}$$

Equation 0-4

$$Combined\ uncertainty = Uncertainty\ 1 + Uncertainty\ 2$$

2. When quantities are added or subtracted, their absolute uncertainties are combined; when quantities are multiplied or divided, their relative (percentage) uncertainties are combined.

We report all uncertainty as relative to align with the approach taken in the National Inventory Report (NIR). This streamlines calculations where quantities are combined with multiplication or division, such that their associated relative uncertainties would be used directly in Equation 0-3a or Equation 0-4. However, when quantities and their associated uncertainties are combined by addition or subtraction, Equation 1-3b can be used (as a modified version of Equation 0-3a).

Equation 1-3b

$$Combined\ uncertainty = \frac{\sqrt{(uncertainty\ 1 \times\ quantity\ 1)^2 + (uncertainty\ 2 \times quantity\ 2)^2}}{|quantity\ 1 + quantity\ 2|}$$

3. When multiplying by a constant, the uncertainty is multiplied by the same constant.

Calculating a coefficient of variation (CV)

When values, such as the GHG reduction effect of a BMP, activity data, and biophysical limit, are extracted from multiple sources or one source provides a range of values for these parameters, we calculate the mean ± %CV before applying to the next step of calculation. Coefficient of variation (%CV), used as the uncertainty of the mean value, is calculated as:

Equation 0-5

$$Coefficient\ of\ variation\ (\%CV) = \frac{standard\ deviation\ of\ selected\ values}{mean\ of\ selected\ values} \times 100\%$$

A.1. BMP: 4R nutrient management

Increasing the accuracy of nitrogen (N) fertilizer applications is a well-documented strategy for reducing direct and indirect N_2O emissions from agricultural soil by improving the N recovery efficiency of crops and reducing losses to the environment (e.g., nitrate (NO_3-N) leaching and ammonia (NH_3-N) volatilization). As a communication strategy, approaches for improving N fertilizer use have been rolled into a single BMP, 4R nutrient management. 4R nutrient management includes applying the (1) right amount of fertilizer from the (2) right source at the (3) right time and to the (4) right place.

1.1. Total activity units

Total activity units, i.e. area of selected field crops (Statistics Canada, 2021a), of annual field crops, potatoes (Statistics Canada, 2021b), berries and fruit trees (Statistics Canada, 2021c), and field vegetables (Statistics Canada, 2021d), were extracted from Statistics Canada and are included in Table A 4.

1.2. Biophysical limit

The biophysical limit for this BMP is not dependent on climate or soil but rather current rates of adoption. Given our knowledge of 4R adoption rates in BC is limited we have applied those from the FCS report (Burton, McConkey, & MacLeod, 2021). The FCS report (Burton, McConkey, & MacLeod, 2021) estimated that the baseline adoption rate for the four crops in their assessment of 4R nutrient management in 2017 was 60%. We assume this baseline adoption ratio is the same for the larger selection of field crops we are using for this BMP analysis, thus the biophysical limit for implementing 4R nutrient management is 40% of total crop area.

1.3. GHG reduction factor

Farmers for Climate Solutions (FCS) (Burton, McConkey, & MacLeod, 2021) evaluated the GHG reduction from the adoption of 4R nutrient management under three level of implementation: Basic, Intermediate, and Advanced. The FCS report determined these emissions reductions for four type of field crops (wheat, canola, potato, and corn). In order to quantify the GHG benefit at a broader scale, we also included other major field crops in BC, such as oats, barley, dry peas, grapes, berries, other tree fruits, and field vegetables (Table A 3). Specific management practices with 4R management include:

- Enhanced efficiency fertilizer by using a nitrification inhibitor, urease inhibitor, and controlled release;
- Reduced rate of N fertilizer based on soil testing and N balance;
- Split fertilizer application for different times of the growing season;
- Variable rate application adjusted for timing and type of crops;
- Subsurface application through banding and/or injection.

The first step to calculating a reduction factor is determining estimates of N_2O emissions from each of the crop types. This is calculated by combining an N application rate with an emission factor. We first extracted the N application rate from ECCC data for each crop type based on the eco-districts of dominant production region. We calculated an uncertainty associated with the N application rate by determining a coefficient of variation (% CV) of recommended N rates from the different eco-districts used to calculate an average N application rate for each crop. We also extracted the emission factor (kg N_2O kg N^{-1}) used in calculating the emissions subcategory 'Agricultural Soil - Direct N_2O Emission' and its uncertainty from the NIR report (Environment and Climate Change Canada, 2020).

Therefore, the annual, direct N_2O emissions from a given crop is calculated as:

$$Direct\ N_2O\ emissions\ (kg\ CO_2e\ ha^{-1}year^{-1}) \\ = N\ application\ rate\ (kg\ N\ ha^{-1}year^{-1}) \times EF(kg\ N_2O\ kg^{-1}N\ ha^{-1}year^{-1}) \\ \times GWP\ of\ N_2O(\frac{298\ kg\ CO_2e}{1\ kg\ N_2O})$$

Taking wheat as an example, the annual, direct N_2O emission is calculated as:

$$Direct\ N_2O\ emission\ (kg\ CO_2e\ ha^{-1}year^{-1}) \\ = 75(kg\ N\ ha^{-1}year^{-1}) \times 0.016\ (kg\ N_2O\ kg^{-1}N\ ha^{-1}year^{-1}) \\ \times GWP\ of\ N_2O\left(\frac{298\ kg\ CO_2e}{1\ kg\ N_2O}\right) = 358\ kg\ CO_2e\ ha^{-1}year^{-1}$$

Table A 1. *Emission factors and direct N_2O emission of major field crops in BC.*

Crop	Region	Ecodistricts	N application rate	N application rate uncertainty	Emission factor (EF)	EF uncertainty	Direct N_2O emission
			kg N ha^{-1} year^{-1}	%	kg N_2O kg^{-1} N ha^{-1} year^{-1}	%	kg CO_2e ha^{-1} year^{-1}
Wheat (spring & winter)	Peace and central BC	#585, #591,#618, #969	75	10%	0.016	27%	358
Canola	Peace and central BC	#585, #591,#618, #970	100	5%	0.016	27%	477
Corn (silage & grain)	Lower Fraser Valley	#959, #960	137	10%	0.016	27%	653
Potato	Southern and coastal BC	#952,#991,#960	80	20%	0.016	27%	381
Oats	Peace and central BC	#585, #591,#618, #969	73	11%	0.016	27%	348
Barley	Peace and central BC	#585, #591,#618, #969	53	12%	0.016	27%	251
Peas (dry)	Southern and coastal BC	#952,#991,#960	40	10%	0.016	27%	191
Grapes	Southern interior BC	#1007, #1010	34	10%	0.016	27%	162
Berries	Lower Fraser Valley	#959, #960	50	10%	0.016	27%	238
Other tree fruits	Southern interior BC	#1007, #1010	100	10%	0.016	27%	477
Field vegetable	Southern and coastal BC	#952,#991,#960	95	10%	0.016	27%	453

Next, a reduction modifier is applied to these direct N_2O emission estimates. The FCS report (Burton, McConkey, & MacLeod, 2021) calculated an N_2O reduction modifier for four types of crop under three levels of implementation (Table A 2). We took the average of the three levels of implementation to have one general N_2O reduction modifier for each crop type used in this analysis for BC. The uncertainty of this N_2O reduction modifier is calculated as the % CV of the three values.

Taking wheat as an example, the N_2O reduction modifier is calculated as:

$$Average\ \ N_2O\ reduction\ modifier = \frac{0.85+0.75+0.65}{3} = 0.75$$

The N_2O reduction modifier uncertainty equals the %CV of the reported values:

$$\boldsymbol{Uncertainty\ of\ N_2O\ reduction\ modifier = \frac{(0.85-0.75)+(0.75-0.75)+(0.75-0.65)}{0.75} = 26.67\%}$$

Table A 2. *N_2O reduction modifiers.*

Levels of implementation	Wheat	Canola	Corn	Potato
Basic	0.85	0.85	0.85	0.95
Intermediate	0.75	0.75	0.75	0.9
Advanced	0.65	0.65	0.65	0.8
Mean	**0.75**	**0.75**	**0.75**	**0.88**
CV%	**27%**	**27%**	**27%**	**7%**

For the additional field crops that we included but were not evaluated by the FCS report, we assumed the FCS N_2O reduction modifiers for barley and oats are the same as for wheat (0.75) and the FCS N_2O reduction modifiers for dry peas and field vegetables are the same as for potato (0.88). The N_2O reduction modifiers of tree fruits, berries, and grapes were assumed to be 0.75 as well. All of these assumed N_2O reduction modifiers were given a large uncertainty of 100% given our lack of crop and regionally specific data.

The GHG reduction factor is then calculated as:

$$GHG\ reduction\ factor\ (t\ CO_2e\ ha^{-1}year^{-1}) = direct\ N_2O\ emission\ from\ soil\ (kg\ CO_2e\ ha^{-1}year^{-1}) \times (N_2O\ reduction\ modifier\ by\ FCS - 1) \times \frac{1\ t}{1000\ kg}$$

Taking wheat as an example, the RF is calculated as:

$$GHG\ reduction\ factor\ (\ t\ CO_2e\ ha^{-1}year^{-1})$$
$$= 358\ (kg\ CO_2e\ ha^{-1}year^{-1}) \times (0.75 - 1) \times \frac{1\ t}{1000\ kg}$$
$$= -0.09\ t\ CO_2e\ ha^{-1}year^{-1}$$

The RF uncertainty is calculated by combining uncertainties using Equation 0-3a**:**

$$Uncertainty\ of\ wheat\ RF =$$
$$\sqrt{(uncertainty\ of\ N\ rate)^2 + (uncertainty\ of\ direct\ N_2O\ EF)^2 + (uncertainty\ of\ N_2O\ reduction\ modifier)^2} =$$
$$\sqrt{(10\%)^2 + (27\%)^2 + (27\%)^2} = 39\%$$

Table A 3 summarizes the calculated RF for all crop types selected in this analysis.

Table A 3. *GHG reduction factor and uncertainty of 4R nutrient management for selected filed crops in BC.*

Crop	**Direct N_2O emission**	**N_2O emission reduction modifier**	**N_2O emission reduction modifier uncertainty**	**GHG reduction factor (RF)**	**RF uncertainty**
	kg CO_2e ha^{-1} yr^{-1}		%	t CO_2e ha^{-1} yr^{-1}	%
Wheat (spring & winter)	358	0.75	27%	-0.09	39%
Canola	477	0.75	27%	-0.12	39%
Corn (silage & grain)	653	0.75	27%	-0.16	39%
Potato	381	0.88	7%	-0.05	34%
Oats	348	0.75	100%	-0.09	104%
Barley	251	0.75	100%	-0.06	104%
Peas (dry)	191	0.88	100%	-0.02	104%
Grapes	162	0.75	100%	-0.04	104%
Berries	238	0.75	100%	-0.06	104%
Other tree fruits	477	0.75	100%	-0.12	104%
Field vegetables	453	0.88	100%	-0.05	104%

1.4. Maximum GHG benefit potential

The maximum GHG benefit potential of 4R nutrient management is calculated as:

$$GHG\ benefit\ of\ 4R\ (kt\ CO_2e\ year^{-1})$$
$$= reduction\ factor\ of\ 4R\ (t\ CO_2e\ ha^{-1}year^{-1}) \times total\ activity\ units\ (ha)$$
$$\times\ biophysical\ limit\ (\%) \times \frac{1\ kt}{1000\ t}$$

As an example, the maximum GHG benefit potential of implementing 4R nutrient management in wheat production is calculated as:

$$GHG\ benefit\ of\ 4R\ (kt\ CO_2e\ year^{-1})$$
$$= -0.09\ (t\ CO_2e\ ha^{-1}year^{-1}) \times 27{,}500\ (ha) \times 40\ \% \times \frac{1\ kt}{1000\ t}$$
$$= -0.98\ kt\ CO_2e\ year^{-1}$$

Table A 4. *GHG benefit of 4R nutrient management for selected field crops in BC.*

Crop	Total activity units	Biophysical limit	GHG reduction factor (RF)	GHG benefit	GHG benefit uncertainty
	ha	%	t CO_2e ha^{-1} yr^{-1}	kt CO_2e yr^{-1}	%
Wheat (spring & winter)	27,500	40%	-0.09	-0.98	39%
Canola	37,300	40%	-0.12	-1.78	39%
Corn (silage & grain)	16,600	40%	-0.16	-1.08	39%
Potato	2,630	40%	-0.05	-0.05	34%
Oats	29,100	40%	-0.09	-1.01	104%
Barley	29,900	40%	-0.06	-0.75	104%
Peas (dry)	26,300	40%	-0.02	-0.24	104%
Grapes	3,974	40%	-0.04	-0.06	104%
Berries	14,128	40%	-0.06	-0.34	104%
Other tree fruits	6,975	40%	-0.12	-0.33	104%
Field vegetables	5,058	40%	-0.05	-0.11	104%
All crops combined	199,465	40%	-0.09	-6.74	24%

The combined maximum GHG benefit of all crops is the sum of the GHG benefit of each crop (-7.2 kt CO_2e year^{-1}). The uncertainty of the combined maximum GHG benefit (± 24%) is calculated using Equation 1-3b**.**

The maximum GHG benefit is then used to calculate a general reduction factor for all crops following:

$$GHG\ reduction\ factor\ (RF, t\ CO_2e\ ha^{-1}year^{-1})$$
$$= \frac{Combined\ maximum\ GHG\ benefit\ (kt\ CO_2e\ year^{-1})}{combined\ total\ activity\ units\ (ha) \times biophysicallimit\ (\%)}$$
$$= -0.09\ t\ CO_2e\ ha^{-1}year^{-1}$$

1.5. Cost of adoption

The FCS economics report (De Laporte, Schuurman, & Weersink, 2021) estimates that the cost of 4R is CA$ 8.35 ha^{-1} under 50% cost sharing program. Therefore, we assumed the full cost of implementing 4R nutrient management would be twice this value: CA$ 16.7 ha^{-1}.

1.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 5. *Summary of qualitative scoring for BMP: 4R nutrient management.*

Criteria	Performance Score	Uncertainty

Long-term GHG benefits	4	Long-term GHG benefits, no decrease in benefits over time	3	Uncertainty is low, based on expert, anecdotal evidence
MRV feasibility	2	The methods are developed but are costly, with high uncertainty and are not widely accepted	N/A	N/A
Soil quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms.	3	Uncertainty is low, based on expert, anecdotal evidence
Water quality / conservation	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms.	4	Uncertainty is low, based on concrete evidence
Air quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms.	4	Uncertainty is low, based on concrete evidence
Biodiversity / pest management	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms.	2	Uncertainty is low, based on non-expert judgement
Financial risks / benefits	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms.	3	Uncertainty is low, based on expert, anecdotal evidence
Adaptation	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms.	3	Uncertainty is low, based on expert, anecdotal evidence
Regulation barriers	3	Requires a permit, but <6-month process, or other paperwork (i.e. taxes) creating a similar burden / obstacle	3	Uncertainty is low, based on expert, anecdotal evidence

1.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *Consideration of the possibility that the reduction in N_2O emissions by using split fertilizer applications could be offset by increased fuel usage*
- *Consider the applicability for orchards and berries where there is a need for machinery to pass without damaging crop (not applicable for cereal, corn, oil seed and some field crops)*

- *For southern BC, implementation of 4R nutrient management is limited due to result of N management being affected simply by animal waste management; some regulations will make it mandatory, but many dairy farmers won't have much room to change. This could result in lower adoption rates. Also, use of slow-release fertilizers or N-inhibitors is not always cost-effective for growers*
- *It would be good to have different emission factors, depending on if N sources is granular (synthetic), or organic, and also if the N is applied to legumes or non-legumes. Could also consider impacts of over-application on some crops (i.e., silage corn and forage grasses)*
- *Regarding cost of adoption, it depends on what management practices are used; slow-release fertilizers and N inhibitors can be at least as costly as the proposed cost of adoption together. Split applications of organic amendments could require building more storage capacity. Overall, the currently proposed cost of adoption values are likely on the low end.*
- *Biggest requirement for many growers (especially organic growers) is support for soil testing, interpretation, and nutrient management plan development, especially given that organic growers won't be able to use things like slow-release fertilizers or nitrification inhibitors.*
- *Other factors, like low soil pH and amelioration of pH to increase nitrogen uptake capacity by plants should also be discussed and be part of the BMP.*
- *There should also be more widespread education and awareness of the acidification of soils through the application of synthetic fertilizers along with meaningful alternatives for fertilizer application (such as livestock integration and cover crops) along with financial support to make those adjustments.*
- *Early adopters and mid-range adopters would already have implemented these practices to a degree. Hence I would expect increased efforts or higher incentives (higher cost shares) to achieve increased adoption in the sector. Current adoption levels are estimated around 60%. My estimate would be an additional 10% increase potential until 2030.*
- *The cost-benefit is not as great as with other potential BMPs. Providing better education and awareness to producers on how they can sustainably reduce synthetic fertilizer*

inputs while maintaining or increasing economic viability of their operation, should be a priority focus.

A.2. BMP: Anaerobic digestion – renewable biogas

Abundant organic residual resources in BC, including animal manure and crop residue from agriculture, municipal, biosolids, food and yard wastes, and biomass from forestry, provide great potential to produce bioenergy as a substitute for fossil fuels. The production of renewable natural gas through anaerobic digestion of organic residuals has been shown to displace natural gas used to produce CO_2-enriched atmospheres (Wang et al 2021). The digestate produced from anaerobic digestion can then be used as an agricultural soil amendment which can offset fertilizer use and incorporate carbon in soils. This BMP synopsis quantifies the GHG emission reduction factor (RF) and GHG benefit potential of producing renewable biogas via anaerobic digestion of animal manure with a focus on dairy and beef cattle manure in BC.

2.1. Total activity units

Total numbers of dairy cows and beef cows under feeding operations in BC are 83,500and 26,000, respectively, as of July, 2018 (Statistics Canada, 2021).

2.2. Biophysical limit

In their analysis of bioenergy options in BC, Wang et al. (2020) estimated that 50 – 75% of the feedstocks they investigated (that include cattle manure, food waste, and crop residues) were considered as easily accessible. Therefore, we estimated the biophysical limit of adoption to be 62.5% (±20%).

2.3. GHG reduction factor

Wang et al. (2020) report biogas produced by anaerobic digestion of animal manure would avoid 70 kg CO_2e GJ^{-1} of natural gas. A life-cycle analysis of biogas production (Berglund and Börjesson 2006) reported that when cow manure of 8% dry matter (DM) content is used to produce biogas, the yield of biogas is 6.2 GJ oven-dried $tonne^{-1}$ (ODT^{-1}). The biogas yield reported by Berglund & Börjesson (2006), was 6.2 GJ ODT^{-1} as the best estimate of the range of results, from 5 to 8.5 GJ ODT^{-1} found in different studies from Sweden. Considering the age of the studies and differences in agriculture practice, an uncertainty of ±50% was assigned to the biogas yield. Dry matter content of cattle manure varies greatly depends on the type of storage system a farm is equipped with (Statistics Canada, 2003). Typical dairy cow manure storage in BC is in liquid or slurry form which contains 1 – 15% DM and beef cow manure collected from feedlot in BC is mostly in solid form that contains 10 – 30% DM (Manitoba Agriculture Food and Rural Initiatives 2009, Smukler et al. 2015). To provide a single value for DM, we used median values and set dairy manure DM content at 8% (±50%) and beef manure DM content at 20% (±50%).

The estimated amount of fresh manure production is 13.4 t cattle^{-1} year^{-1} by beef cow and 22.7 t cattle^{-1} year^{-1} by dairy cow (Hofmann and Beaulieu 2001). Therefore, the GHG RF is calculated as:

$$GHG\ reduction\ factor\ (t\ CO_2e\ 1000\ head^{-1}year^{-1}) = GHG\ reduction\ of\ displacing\ natrual\ gas\ (kg\ CO_2e\ GJ^{-1}) \times biogas\ yield\ (GJ\ ODT^{-1}) \times fresh\ manure\ production\ (t\ cattle^{-1}year^{-1}) \times \%\ dry\ matter\ content \times 1000\ cattle \times \frac{1\ t}{1000\ kg} \times reduction\ modifier$$

For beef cows this is calculated as:

$$RF_{Beef} = 70\ kg\ CO_2e \frac{1}{GJ} \times 6.2 \frac{GJ}{ODT} \times 13.4\ \frac{1}{cattle \times year} \times 20\%\ \frac{ODT}{ton} \times 1000\ cattle \times \frac{1\ t}{1000\ kg} \times (-1) = -1166.94\ t\ CO_2e\ 1000\ head^{-1}year^{-1}$$

For dairy cows this is calculated as:

$$RF_{Dairy} = 70\ kg\ CO_2e \frac{1}{GJ} \times 6.2 \frac{GJ}{ODT} \times 22.7\ \frac{1}{cattle \times year} \times 8\%\ \frac{ODT}{ton} \times 1000\ cattle \times \frac{1\ t}{1000\ kg} \times (-1) \times (-1) = -788.4\ t\ CO_2e\ 1000\ head^{-1}year^{-1}$$

The uncertainties are combined using Equation 0-3a**:**

$$RF\ uncertainty = \sqrt{(uncertainty\ of\ biogas\ yield)^2 + (uncertianty\ of\ manure\ dry\ matter\ content)^2} = \sqrt{(50\%)^2 + (50\%)^2} = 71\%$$

2.4. Maximum GHG benefit potential

The GHG reduction benefit of renewable biogas produced by anaerobic digestion of cattle manure is calculated as:

$$GHG\ benefit\ (kt\ CO_2e\ year^{-1}) = RF\ (t\ CO_2e\ 1000\ head^{-1}year^{-1}) \times totalactivity\ units\ (1000\ cattle) \times biophysical\ limit\ (\%) \times \frac{1\ kt}{1000\ t}$$

For dairy cows:

$$GHG\ benefit\ (kt\ CO_2e\ year^{-1}) = -788.4\ t\ CO_2e\ 1000\ head^{-1}year^{-1} \times 83.5\ (1000\ cattle) \times 62.5\% \times \frac{1\ kt}{1000\ t} = -41.14\ kt\ CO_2e\ year^{-1}$$

For beef cows:

$$GHG\ benefit\ (kt\ CO_2e\ year^{-1}) = -1166.9\ t\ CO_2e\ 1000\ head^{-1}year^{-1} \times 26\ (1000\ cattle) \times 62.5\% \times \frac{1\ kt}{1000\ t} = -18.96\ kt\ CO_2e\ year^{-1}$$

The uncertainties are combined using Equation 0-3a**:**

$$GHG\ benefit\ uncertainty = \sqrt{(uncertainty\ of\ RF)^2 + (uncertainty\ of\ biopyhsical\ limit)^2}$$

$$= \sqrt{(71\%)^2 + (20\%)^2} = 74\%$$

The combined GHG reduction benefit of both dairy cows and beef cows' is calculated as:

$$Combined\ GHG\ benefit = GHG\ benefit\ of\ dairy\ cows + GHG\ benefit\ of\ beef\ cows$$
$$= (-41.14\ kt\ CO_2e\ year^{-1}) + (-18.96kt\ CO_2e\ year^{-1})$$
$$= -60.1\ kt\ CO_2e\ year^{-1}$$

The uncertainties are combined using Equation 1-3b:

$$Uncertainty\ of\ combined\ GHG\ benefit$$
$$= \frac{\sqrt{(GHG\ benefit\ of\ dairy\ cows \times uncertainty)^2 + (GHG\ benefit\ of\ beef\ cows \times uncertainty)^2}}{|Combined\ GHG\ benefit|}$$
$$= \frac{\sqrt{(-41.14 \times 74\%)^2 + (-18.96 \times 74\%)^2}}{60.1} = 55\%$$

2.5. Cost of adoption

Wang et al. (2021) estimated that the cost to process one ton of manure DM, including capital cost of anaerobic digestion facility and production cost (e.g. cost of manure, transportation, and operation), ranges from CA$ 930 to CA$1,360. Assuming there is no policy changes that would incentivize renewable natural gas, the revenue from selling biogas and digestion by-product (i.e. fertilizer) is a net loss range from CA$ 140 to CA$ 240 per ton DM of manure. Therefore, the annual adoption cost is calculated as:

$$Annual\ adoption\ cost\ (\$\ 1000\ head^{-1}year^{-1})$$
$$= average\ revenue\ (\$\ t\ DM^{-1})$$
$$\times\ annual\ fresh\ manure\ production\ of\ 1000\ cattle\ (t\ 1000\ head^{-1}year^{-1})$$
$$\times\ DM\%$$

For dairy cows:

$$Annual\ adoption\ cost\ (\$\ 1000\ head^{-1}year^{-1})$$
$$= \frac{140 + 240}{2}\ (\$\ t\ DM^{-1}) \times \frac{22.7\ t}{cattle \times year} \times 1000\ cattle \times 8\%\ \frac{DM}{ton}$$
$$= \$34{,}5131\ 1000\ head^{-1}year^{-1}$$

For beef cows:

$$Annual\ adoption\ cost\ (\$\ 1000\ head^{-1}year^{-1})$$
$$= \frac{140+240}{2}\ (\$\ t\ DM^{-1}) \times \frac{13.4\ t}{cattle \times year} \times 1000\ cattle \times 20\%\ \frac{DM}{ton}$$
$$= \$51{,}0872\ 1000\ head^{-1}year^{-1}$$

2.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section *3.4.2. Quantitative scoring in the MCF*,** and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 6. *Summary of qualitative scoring for BMP: Anaerobic digestion.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	4	Long-term GHG benefits, no decrease in benefits	2	Uncertainty is low, based on non-expert judgement
MRV feasibility	2	The methods are developed but are costly, with high uncertainty and are not widely accepted	N/A	N/A
Soil quality	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Water quality / conservation	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	2	Uncertainty is low, based on non-expert judgement
Air quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	2	Uncertainty is low, based on non-expert judgement
Biodiversity / pest management	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	2	Uncertainty is low, based on non-expert judgement

Adaptation	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	2	Uncertainty is low, based on non-expert judgement
Regulation barriers	2	Requires a permit; 6 months to 2 year approval process; or other paperwork (i.e. taxes) creating a similar burden / obstacle	2	Uncertainty is low, based on non-expert judgement

2.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *Estimated adoption potential of 25% for beef feedlots.*
- *For beef cattle production there should be more clarity that digesters would only be a discussion point for confined cattle operations such as feedlots. Rather than promoting anaerobic digestion there should be a focus on a) promoting the extensive raising of beef to be able to utilize cattle as soil improvement tools (as outlined in regenerative ag principles) and b) if cattle are held in confinement that the manure could alternatively be used as a valuable nutrient source for nearby land. Rather than digesters, there may be opportunities to compost manure and increase the usability as an alternative fertilizer product on a nearby landbase. Policies and regulations should be reviewed to support such practices along with application guidelines to prevent overapplication of phosphorus.*
- *The adoption of these technologies come with a significant cost. I would want to see an exploration of alternative beef manure processing that is more in line with regenerative agriculture (using manure as a fertility alternative to synthetic fertilizer) versus the production of biogas. Again, this applies to beef production only and would be more applicable in more rural areas where feedlot production occurs.*
- *The anaerobic digester microbiome is sensitive to feedstock changes - inconsistent food waste and crop residues (quality, quantity, and availability) significantly impact biogas production. The cost and fuel consumed to transport/stockpile the feedstocks to anaerobic digestor facilities may negate the increased biogas production. Also note that municipal biosolids cannot be spread on ag land.*

- *A certain economy of scale is needed for anaerobic digestion to be economically viable, i.e., minimum herd size plus close proximity to a Fortis BC natural gas line.*

A.3. BMP: Best-in-class Greenhouse Retrofit

Energy consumption for heating and lighting in greenhouse production is a major source of agricultural GHG emissions that falls under the NIR category of "Energy". A best-in-class (BIC) greenhouse is defined as an existing greenhouse that underwent extensive retrofit to achieve the most cost-effective energy efficiency attainable with available technologies.

Specific improvements for the BIC retrofit include:

- Condensing Boilers
- Greenhouse Envelope Improvement
- LED Grow Lights
- Motor with Variable Speed Drives (VSDs)
- Electrification of Space Heating
- Greenhouse Curtains
- Process Cooling
- Compressed Air
- Water Savings

ICF Canada conducted a benchmark study on the GHG emission intensity of the greenhouse sector in BC with focus on vegetable and cannabis production (ICF Canada, 2020); more details about the BIC retrofit can be found in the IFC report. This BMP synopsis uses results from the ICF report to calculate a GHG emission reduction factor (RF) and the maximum GHG benefit potential for adoption of BIC greenhouse retrofit.

3.1. Total activity units

Total greenhouse area reported by Statistics Canada was 494 ha in 2019 (Statistics Canada, 2021), of which 274 ha were vegetables and fruits operation and 136 ha were flower and plants operation, excluding cannabis (Statisitics Canada, 2021b).

3.2. Biophysical limit

We assume 100% of greenhouse operation in BC can adopt the BIC retrofit, i.e. there is no biophysical limit.

3.3. GHG reduction factor

According to the ICF report (ICF Canada, 2020), the baseline GHG emissions of greenhouses in BC are 282 t CO_2e acre^{-1} year^{1} for vegetable and 314 t CO_2e acre^{-1} year^{1} for cannabis. The GHG reduction effect of BIC retrofitting is -17 ± 9% and -9 ± 6% for vegetable and cannabis, respectively (ICF Canada, 2020). Uncertainties of these emission reduction value are the CV% of reported range values for different types of greenhouse operation, e.g. unlit vs. lit. (ICF Canada, 2020) The ICF report did not provide uncertainty estimation associated with the baseline emission. We extracted the uncertainty value of *fuel combustion – other sector* (IPCC Source Category 1.A.4) (Environment and Climate Change Canada, 2020).

The baseline emission intensity is first converted to a hectare basis: t CO_2e ha^{-1} year^{1} by multiplying 2.47. The RF is then calculated as:

$$RF(t\ CO_2e\ ha^{-1}year^{-1}) = baseline\ emission\ (t\ CO_2e\ acre^{-1}year^{-1}) \times hectare\ conversion(\frac{2.47\ acre}{ha}) \times reduction\ effect\ of\ BIC\ retrofit$$

$$RF_{vegetable} = baseline\ emission\ \times hectare\ conversion \times reduction\ effect\ of\ BIC\ retrofit = 282\ t\ CO_2e\ acre^{-1}year^{-1} \times 2.47\frac{acre}{ha} \times (-17\%) = -118.41\ t\ CO_2e\ ha^{-1}year^{-1}$$

$$RF_{cannabis} = baseline\ emission\ intensity\ \times hectare\ conversion \times reduction\ effect\ of\ BIC\ retrofit = 314\ t\ CO_2e\ acre^{-1}year^{-1} \times 2.47\frac{acre}{ha} \times (-9\%) = -69.8\ t\ CO_2e\ ha^{-1}year^{-1}$$

Cannabis operations are not included in the activity data published by Statistics Canada. We assumed that flower and plants operation has an energy consumption level between vegetable and cannabis. Therefore, the RF of flower and plants operation is the average of $RF_{Vegetable}$ and $RF_{Cannabis}$, -95.69 t CO_2e ha^{-1} $year^{1}$ with uncertainty of ± 8% (Table A 7).

Table A 7. *Baseline GHG emission, reduction factor, and activity units of different types of greenhouse operation.*

Crop	Baseline emission	Baseline emission uncertainty	Emission reduction	Emission reduction uncertainty	RF	RF uncertainty	Total activity units
	t CO_2e ha^{-1} yr^{-1}	%	%	%	t CO_2e ha^{-1} yr^{-1}	%	ha
Vegetable	696.54	2%	17%	9%	-118.41	9%	274
Flower and plants	736.06	2%	13%	8%	-95.69	8%	136
Cannabis	775.58	2%	9%	6%	-69.80	6%	-

3.4. Maximum GHG benefit potential

The maximum GHG benefit potential is calculated as:

$$Max. GHG\ benefit\ potential = RF \times total\ activity\ units \times biophysical\ limit \times \frac{1\ kt}{1000\ t}$$

$$Max. GHG\ benefit\ potential\ from\ vegetable\ and\ fruit\ operation$$

$$= -118.41\ t\ CO_2e\ ha^{-1}year^{-1} \times 274\ ha \times 100\% \times \frac{1\ kt}{1{,}000\ t}$$

$$= -32.44\ kt\ CO_2e\ year^{-1}$$

$$Max. GHG\ benefit\ potential\ from\ flowers\ and\ plants\ operation$$

$$= -95.69\ t\ CO_2e\ ha^{-1}year^{-1} \times 136\ ha \times 100\% \times \frac{1\ kt}{1{,}000\ t}$$

$$= -13.02\ kt\ CO_2e\ year^{-1}$$

3.5. Cost of adoption

According to BC Environmental Farm Plan (British Columbia Agriculture Research and Development Corporation 2020), the cost of several major BIC retrofitting practices are covered or partially covered by the EFP (Table A 8). We used the program incentive to back calculate the projected cost of these practices and the estimated annual cost of BIC retrofitting is CA$ 34,542 per greenhouse. The average size of a greenhouse operation in BC is 0.78 ha (Statisitics Canada, 2021b).

Thus, the cost of BIC retrofitting is calculated as:

$$Cost\ of\ BIC\ retrofit\ (CA\$\ ha^{-1} year^{-1}) = \frac{Annual\ cost\ (CA\$)}{Average\ greenhouse\ size\ (ha)}$$

$$= \frac{34{,}542 (CA\$)}{0.78\ (ha)} = CA\$\ 44{,}284.6$$

Table A 8. *Summary of costs from EFP BMP program used to calculate BIC greenhouse retrofit cost of adoption.*

BIC retrofitting items	**Costs covered**	**% covered by EFP**	**Projected total costs**
	CA$	**%**	**CA$**
Energy consult	3,000	100%	3,000
Replacement of fossil-fuel dependent space heating with renewable heating	30,000	30%	100,000
Thermal energy efficiency improvements (i.e. thermal curtains)	30,000	30%	100,000
Lighting efficiency improvements	10,000	30%	33,333
Engineering design work and technical feasibility	20,000	50%	40,000
		TOTAL	**276,333**
		Annual cost by 2030	**34,542**

3.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 9. *Summary of qualitative scoring for BMP: BIC greenhouse retrofit.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	4	Long-term GHG benefits, no decrease in benefits over time	2	Uncertainty is low, based on non-expert judgement
MRV feasibility	4	Methods are cost-effective, with low uncertainty specifically for BC	N/A	N/A
Soil quality	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Water quality / conservation	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Air quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	2	Uncertainty is low, based on non-expert judgement
Biodiversity / pest management	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	2	Uncertainty is low, based on non-expert judgement
Adaptation	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	2	Uncertainty is low, based on non-expert judgement

A.4. BMP: Cattle feed additive: 3-nitrooxypropanol (3NOP)

Enteric fermentation is a major source of agricultural GHG emissions and in BC these emissions are nearly entirely from dairy and beef cattle (see our *Report 1: BC Agriculture GHG Emission Profile Analysis*). The feed additive 3-nitrooxypropanol (3NOP) is a synthetic compound which inhibits methanogenic bacteria from performing the final step of methane production in livestock's rumen, thus reducing enteric methane production. We have determined the GHG benefit potential of this BMP for the two primary livestock sectors responsible for enteric fermentation emissions. BMP GHG reduction factors (RF) and activity data (head of livestock) were calculated separately for dairy and beef. The RF data was based on studies administering the feed additive at 1 to 3g 3NOP day^{-1} directly added to grain rations.

4.1. Total activity units

For this BMP it is assumed that most dairy cows are fed daily grain rations for the majority of their time. Therefore, dairy cow population activity data is the total number of dairy cows reported at July 2018 (Statistics Canada Table 32-10-0424-01); this is 83,500 dairy cows. Most of BCs beef cattle are on cow calf operations. Therefore, instead of using a total number of beef cattle for the province (~441 000), we have used the number of beef cattle on feeding operations (26, 000) as reported in the Statistics Canada livestock survey (Statistics Canada Table 32-10-0130-01).

4.2. Biophysical limit

There is ongoing research looking at how 3NOP can be used in grazing operations. However, the 3NOP feed additive has thus far largely been developed and studied as an addition to grain rations and these are the studies that have been used in this BMP synopsis. Therefore, cattle in BC that would be eligible for 3NOP use must be on farms where cattle are being fed a daily grain ration (i.e., in feeding operations) and not in grazing systems (i.e., cow calf operations). Therefore, only data for cattle presumed to be in feeding operations was extracted from Statistics Canada, and a 100% biophysical limit applied to them.

4.3. GHG reduction factor

The following examples show RF calculations for dairy cattle, and the same calculations were made for beef cattle but are not shown here. The example starts with specific data examples from Van Wesemael (2019) and then calculates an overall RF for dairy cattle by combing these data from Van Wessemail (2019) with data from two other studies (Schilde et al. 2021, Melgar et al. 2021). RF data for both dairy and beef cattle are included in Table A 10.

1. **Calculate a RF (g CH_4 day^{-1}) from each treatment within a study**

The RF is calculated as the difference in emissions between a "business as usual" control (CON) and a 3NOP BMP treatment (TMT). The uncertainty associated with this RF is then calculated by adding together the absolute uncertainties (standard errors in original units, g) from the CON and TMT using Equation 0-4 for combining non-independent errors.

For example, from Van Wesemael (2019), CON was feeding the typical ration without 3NOP, and TMT 1 was feeding the typical ration plus 1.6 g 3NOP day^{-1}. Emissions measured from **CON** in this study was 525 ± 12.3 g CH_4 day^{-1} and from **TMT 1** was 380 ± 12.3 g CH_4 day^{-1}, and uncertainties are combined using Equation 0-4 such that:

$$\boldsymbol{TMT\ 1\ RF}\ (g\ CH4\ day^{-1}) = (380\ g\ CH4\ day^{-1} - 525\ g\ CH4\ day^{-1}) \pm (12.3\ g\ CH4\ day^{-1} + 12.3\ g\ CH4\ day^{-1}) = -145 \pm 24.6\ g\ CH4\ day^{-1}$$

This is then converted into a percentage reduction relative to the "business as usual" **CON** by dividing this change in emissions from the emissions from **CON**; the same is done with the associated uncertainty:

$$\boldsymbol{TMT\ 1\ RF}\ (\%) = -\frac{145\ g\ CH4\ day^{-1}}{525\ g\ CH4\ day^{-1}} \pm \frac{24.6\ g\ CH4\ day^{-1}}{525\ g\ CH4\ day^{-1}} = -28 \pm 4.7\ \%$$

The same process is performed with **TMT 2** from the same study, which also administered 1.6 g 3NOP day^{-1}, but in pelletized form (data shown in **Table 10**).

2. **Average TMT RFs within a given study**

These TMT RFs and their associated uncertainties are combined using simple averaging and error propagation according to Equation 0-4 (for combining non-independent errors). For example, calculating a BMP RF from the **TMT 1** and **TMT 2** in Van Wesemael, (2019):

$$\boldsymbol{BMP\ RF_1}\ (\%) = \left(\frac{-28\ \% \ +\ -23\ \%}{2} \pm \frac{4.7\ \% \ +\ 4.7\ \%}{2}\right) = -25 \pm 4.7\ \%$$

This is BMP RF_1 because each study will give a different RF (i.e. RF_1, RF_2, etc.) for a BMP, which are then combined in the next step.

3. **Average RFs from multiple, independent studies**

The BMP RFs from various studies (calculated in Steps 1 and 2) are combined into one BMP RF for dairy cattle through simple averaging:

$$\boldsymbol{BMP\ RF} = \frac{(RF_1 +\ RF_2 + RF_3 \ldots + \cdots n)}{n} = \frac{(-25\% +\ -27\% +\ -27\%)}{3} = -26\ \%$$

The uncertainties are combined using Equation 0-3a**:**

$$\boldsymbol{BMP\ RF\ uncertainty}$$
$$= \sqrt{(Uncertainty\ of\ RF_1)^2 + (Uncertainty\ of\ RF_2)^2 \ldots + \ldots (Uncertainty\ of\ RF_n)^2}$$
$$= \sqrt{(4.7\%)^2 + (3.0\%)^2 + (1.0\%)^2} = 1.9\ \%$$

4. **Convert RF (%) to RF (t CO_2e 1000 hd^{-1} $year^{-1}$)**

Using a daily methane emission factor (EF) for dairy cows from the NIR of 139.6 kg CH4 hd^{-1} $year^{-1}$, the BMP RF is calculated per 1000 head of cattle, and converted from kg to metric t and CH_4 to CO_2e:

$$\boldsymbol{BMP\ RF}\ (t\ CO2e\ 1000\ hd^{-1}year^{-1})$$
$$= BMP\ RF\ (\%) * NIR\ Dairy\ Cow\ EF\ (kg\ CH4\ hd^{-1}\ year^{-1})$$
$$= -26.4953\ \% * 139.6\ kg\ CH4\ hd^{-1}\ year^{-1} * \frac{25\ kg\ CO2e}{1\ kg\ CH4}$$
$$= -924.7\ t\ CO2e\ 1000\ hd^{-1}year^{-1}$$

The uncertainties are combined using Equation 0-3a**:**

$$BMP\ RF\ uncertainty\ = \sqrt{(Uncertainty\ of\ RF)^2 + (Uncertainty\ of\ EF)^2}$$
$$= \sqrt{(22\%)^2 + (7.6\%)^2} = 23\ \%$$

5. Summarize BMP RF data to transfer into BMP database

The BMP RF values to transfer into the BMP database for dairy cattle are:

$$\boldsymbol{-924.7}\ t\ CO2e\ 1000\ hd^{-1}\ year^{-1} \pm \boldsymbol{23}\ \%$$

Additional notes regarding BMP GHG calculations

1. The following data from Reynolds et al. (2014) is included in the literature spreadsheet but was excluded from calculations because the 3NOP was injected into the rumen, which is now a refuted practice:

X 4. Reynolds, 2014: - 6% from 0.5g 3-NOP/day injected into rumen before eating TMR

X 5. Reynolds, 2014: -10% from 2.5g 3-NOP/day, injected into rumen before eating TMR

Table A 10. *Summary of data and calculations for BMP reduction factors for 3NOP for dairy and beef cattle.*

	Measured Emissions	Unc.	Emission reduction	Unc.	Tmt reduction factor (RF)	Tmt RF uncertainty	NIR Emission Factor (EF)	NIR EF uncertainty	Reduction factor (RF)	RF uncertainty
	g CH4/day				%		kg CH_4 head^{-1} yr^{-1}	%	t CO_2e 1000 hd^{-1} yr^{-1}	%
Dairy cattle	**n/a**	**n/a**	**n/a**	**n/a**	**26**	**1.9**	**139.6**	**22%**	**924.7**	**23%**
(Van Wesemael et al. 2019)	n/a	n/a	n/a	n/a	25	4.7				
CON	525	12.3	n/a	n/a	n/a	n/a				
TMT 1	380	12.3	145	24.6	28	4.7				
TMT 2	403	12.3	122	24.6	23	4.7				
(Melgar et al. 2021)	n/a	n/a	n/a	n/a	27	3.0				
CON	411	6.1	n/a	n/a	n/a	n/a				
TMT 1	301	6.1	110	12.2	27	3.0				
(Schilde et al. 2021)	n/a	n/a	n/a	n/a	27	1.0				
CON 1	373	1.92	n/a	n/a	n/a	n/a				
TMT 1	291	1.92	82	3.84	22	1.0				
CON 2	365	1.92	n/a	n/a	n/a	n/a				
TMT 2	246	1.92	119	3.84	33	1.1				
Beef cattle	**n/a**	**n/a**	**n/a**	**n/a**	**51**	**11.2**	**120.5**	**22%**	**1521.6**	**31%**
(Romero-Perez 2015)	n/a	n/a	n/a	n/a	59	9				
CON	157.93	6.79	n/a	n/a	n/a	n/a				
TMT	64.49	6.79	93.44	13.58	59	8.6				
(Romero-Perez et al. 2014)	n/a	n/a	n/a	n/a	25	22.1				
CON	206.8	22.9	n/a	n/a	n/a	n/a				
TMT 1	199.2	22.9	7.6	45.8	4	22.1				
TMT 2	180.2	22.9	26.6	45.8	13	22.1				
TMT 3	129.1	22.9	77.7	45.8	38	22.1				
(Alemu et al. 2021)	n/a	n/a	n/a	n/a	67	23.6				
CON	126.4	14.94	n/a	n/a	n/a	n/a				
TMT 1	54.8	14.94	71.6	29.88	57	23.6				
TMT 2	28.6	14.94	97.8	29.88	77	23.6				
TMT 3	41.2	14.94	85.2	29.88	67	23.6				

4.4. Maximum GHG benefit potential

We assumed that 100% of dairy cows and 100% of beef cows on feeding operations could be administered 3NOP as a BMP to reduce enteric fermentation emissions. Therefore, the maximum potential reduction is calculated as:

$$Dairy\ max. GHG\ benefit\ potential$$

$$= RF\ dairy\ x\ dairy\ activity\ units \times \frac{1\ kt}{1000\ t}\ x\ 100\%\ biophysical\ limit$$

$$= -924.7\ x\ 83.5\ x\ \frac{1}{1000} = -77.21\ kt\ CO2e\ year^{-1} \pm 23\%$$

$$Beef\ max. GHG\ benefit\ potential$$

$$= RF\ beef \times beef\ activity\ units \times \frac{1\ kt}{1000\ t}\ x\ 100\%\ biophysical\ limit$$

$$= -1521.6\ x\ 26\ x\ \frac{1}{1000} = -39.56\ kt\ CO2e\ year^{-1}\ \pm 31\%$$

4.5. Cost of adoption

The 3NOP feed additive is not yet approved for use in Canada, so cost estimates are highly preliminary and entirely sourced from grey literature at this point. One source estimates \$50 $head^{-1}$ $year^{-1}$ (Ecosystem Marketplace 2017) and another estimate is \$10 $head^{-1}$ $year^{-1}$ (Schilliger 2017). Therefore, we have included an average of these two for a \$30 $head^{-1}$ $year^{-1}$ cost of adoption estimate.

4.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section *3.4.2. Quantitative scoring in the MCF*,** and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 11. *Summary of qualitative scoring for BMP: 3NOP feed additive.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	4	Very positive impacts: Long term GHG benefits, no decrease in benefits over time	2	Moderate uncertainty: Uncertainty is low, based on non-expert judgement
MRV feasibility	2	Somewhat operational: The methods are developed but are costly, with high uncertainty and are not widely accepted	N/A	N/A
Soil quality	2	Neutral: This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Low uncertainty: Uncertainty is low, based on expert, anecdotal evidence
Water quality / conservation	2	Neutral: This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Low uncertainty: Uncertainty is low, based on expert, anecdotal evidence
Air quality	2	Neutral: This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Low uncertainty: Uncertainty is low, based on expert, anecdotal evidence
Biodiversity / pest management	2	Neutral: This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Low uncertainty: Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	2	Neutral: This co-benefit will not be impacted by this practice, or harms and benefits offset	2	Moderate uncertainty: Uncertainty is low, based on non-expert judgement
Adaptation	2	Neutral: This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Low uncertainty: Uncertainty is low, based on expert, anecdotal evidence

4.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *Hard to estimate adoption potential without 3NOP being on the market yet, but likely something around 25%.*
- *I could easily see a very high adoption for a more general BMP, such as more 'chemical class specific' (i.e., ionophores - approved for dairy or beef diets). Although the inclusion of ionophores in Canadian dairy and beef diets in at a decent level, the offering of a*

financial incentive to ensure an ionophore is included in the diet would be well received. Once 3NOP is approved & if it shows higher CH_4 reducing potential than other ionophores already on the market, provided its priced right and economical, we could see dairy & beef nutritionists advising their clients to consider switching to 3NOP.

- *Contact 'Royal DSM', which is a multinational nutrition company that has filed for commercial registration for 3NOP under the trademark 'Bovaer'. Most likely, Royal DSM has filed for a joint approval process with both Canada and the USA to use 3NOP in cattle diets (including dairy). It would be beneficial to check with Royal DSM for some of their data - as it pertains to 3NOP and what levels of CH_4 reduction they showed in their trials when 3NOP was fed to dairy and beef cattle.*
- *Important to note: Improved feed efficiency, improved growth, increased milk yield, and reduced methane production have long been proven (over 30 years) by various ionophores that have been approved for inclusion in cattle (dairy and beef) diets in Canada (e.g., Monensin, Rumensin - CRC = controlled release capsules). Canadian dairy nutritionists have been including these additives in many dairy diets to improve feed efficiency, and indirectly reducing methane emissions.*
- *The current qualitative scoring for co-benefit assumes that 3NOP does not negatively impact production, carcass quality, fertility/conception rates, lameness, overall health, longevity of the animals.*

A.5. BMP: Cover crops

The environmental and agronomic benefits of growing cover crops during non-production seasons as a beneficial management practice (BMP) to reduce bare fallow has been widely studied (Abdalla et al. 2019). Planting cover crops for GHG benefits is one of the five BMPs that Farms for Climate Solutions (FCS) selected and performed an in-depth analysis on (Burton, McConkey, & MacLeod, 2021). In this BMP synopsis, data for GHG benefits of cover crops are largely taken from the FCS report, and any exceptions to this are noted. GHG benefits from cover crops are calculated from three pathways (increased SOC, and reduced direct and indirect N_2O emissions), which are summed to estimate the BMP GHG emission reduction factor (RF). The BMP GHG RF is then combined with activity data for major annual field crops in BC (i.e., total seeded area) to calculate the maximum GHG benefit potential of adopting a cover crop BMP in British Columbia.

5.1. Total activity units

Total seeded area for annual field crops that would be suitable for cover crops and used in the FCS report were extracted from agriculture and food dataset of Statistics Canada (Statistics Canada, 2021a) The FCS report did not evaluate cover crops use for field vegetables, which represent a sizable area in BC (5,058 ha), so we also included this as a previous cash crop category. We assigned each previous cash crop to the two dominant climate zones in BC (Black soil & Montane Cordillera and Pacific Maritime) where they are likely to be grown (Table A 12).

Table A 12. *Effect of cover crops on GHG emissions following different types of annual field crops in BC.*

Previous cash crop	Climate zone	Crop seeded area	Max. adoption potential	Legume ratio in cover crops (Flegume)	Δ Soil carbon sequestration	Δ Indirect N2O (Flegume = 100%)	Δ Direct N2O (Flegume = 100%)
		ha	%		t C $ha^{-1}yr^{-1}$	kg N_2O $ha^{-1}yr^{-1}$	kg N_2O $ha^{-1}yr^{-1}$
Winter cereal (wheat & rye)	Black soil & Montane Cordillera	12,900	90%	1	0.16	-0.28	-1.1
Peas	Pacific Maritime	26,300	95%	0	0.51	-0.36	0.89
Barley	Black soil & Montane Cordillera	29,900	85%	1	0.14	-0.59	-1.86
Oats	Black soil & Montane Cordillera	29,100	85%	1	0.14	-0.59	-1.86

Fallow replacement	Black soil & Montane Cordillera	19,100	100%	1	0.48	-0.99	-4.11
Spring canola	Black soil & Montane Cordillera	37,300	75%	1	0.11	-0.26	-1.13
Silage corn	Pacific Maritime	15,800	85%	0	0.45	-0.66	1.61
Spring cereal (wheat & rye)	Black soil & Montane Cordillera	18,600	75%	1	0.11	-0.26	-1.13
Potato	Pacific Maritime	2,630	70%	0	0.26	-0.81	2.01
Field vegetables	Pacific Maritime	5,058	80%	-*	0.49*	0.07*	0.9*

*Effects of cover crops on field vegetable were extracted from different sources. FCS calculation (equation 2-1a&b) do not apply to these values.

5.2. Biophysical limit

Biophysical limits for maximum adoption potential (% of total crop area) were also extracted from the FCS report for the two climate zones appropriate for BC (Burton, McConkey, & MacLeod, 2021). We applied the maximum adoption potential reported by the FCS report as the biophysical limit of adopting cover crops as a BMP (Burton, McConkey, & MacLeod, 2021). The biophysical limit for field vegetable, 80%, is an estimate based on our best knowledge (Table A 12).

5.3. GHG reduction factor

The reduction factor for cover crops was calculated primarily using the approach reported by FCS. FCS calculated the effect of cover crops on GHG emissions for three major pathways: (1) change in soil C (ΔSC_{seq}); (2) change in direct N_2O emission ($\Delta dirN_2O$); and (3) change in indirect N_2O emission ($\Delta indirN_2O$) (Burton, McConkey, & MacLeod, 2021). These effects were specific to the previous cash crop and climate zone (Table A 12).

We developed our own calculations for the 'field vegetables' previous cash crop category. We extracted the average non-legume cover crop effect on GHG emission (i.e., change of direct and indirect N_2O emissions) reported from a review of 13 studies by Abdalla et al. (2019). Non-legume cover crops reduce direct N_2O emissions by 0.9 ± 0.11 t CO_2e ha^{-1} $year^{-1}$ and increase indirect N_2O emissions by 0.07 ± 0.28 t CO_2e ha^{-1} $year^{-1}$ (Abdalla et al., 2019). For the effect of cover crops on soil C sequestration (Cseq), we used 0.49 t C ha^{-1} $year^{-1}$ (Poeplau et al. 2015), which is the soil Cseq rate of a ryegrass cover crop in Washington, USA, where climate and soil properties are similar to Pacific Maritime zone in BC.

Cover crop effects on GHG emissions given by FCS (Table A 12) are calculated using two conversion functions (Equation 2-1a and 2-1b) which adjust the values based on different ratio of legume species seeded in the cover crop mix. In our analysis, to achieve the highest possible GHG benefit, peas, silage corn, and potato were assigned non-legume cover crop (i.e., F_{legume} = 0) and the rest of the cash crops were assigned with 100% legume cover crops (i.e., F_{legume} = 1).

Equation 2-1a

$$Legume\ ratio\ correction\ factor\ for\ indirect\ N2O\ emission\ = 0.67 \times \left(1 - F_{legume}\right) + 1$$

Equation 2-1b

$$Legume\ ratio\ correction\ factor\ for\ direct\ N2O\ emission\ = -1 + \frac{F_{legume}}{0.5}$$

As an example, the GHG reduction achieved by increasing soil Cseq and reductions in indirect and direct N_2Oemissions by planting a legume cover crop after a winter cereal cash crop is calculated as:

$$RF_{SCseq} = \Delta\mathrm{SCseq} \times\ CO_2\, conversion\ \times\ negative\ emission\ reduction\ modifier$$

$$= 0.16\, t\, C\ \mathrm{ha^{-1}year^{-1}} \times \frac{44\ \mathrm{CO_2e}}{12\ C} \times (-1) = -0.59\, t\ \mathrm{CO_2e\ ha^{-1}year^{-1}}$$

$$RF_{indirN2O} = \Delta\mathrm{indir}N_2\mathrm{O} \times \text{legume ratio correction factor} \times\ GWP\ of\ N_2\mathrm{O} \times \frac{1\, t}{1000\, kg}$$

$$= -0.28\, kg\ \mathrm{CO_2e\ ha^{-1}year^{-1}} \times 1 \times 298 \frac{\mathrm{kg\ CO_2e}}{kg\ N_2O} \times \frac{1\, t}{1000\, kg}$$

$$= -0.08\, t\ \mathrm{CO_2e\ ha^{-1}year^{-1}}$$

$$RF_{dirN2O} = \Delta\mathrm{dir}N_2\mathrm{O} \times \text{legume ratio correction factor} \times\ GWP\ of\ N_2\mathrm{O} \times \frac{1\, t}{1000\, kg}$$

$$= -1.1\, kg\ \mathrm{CO_2e\ ha^{-1}year^{-1}} \times 1 \times 298 \frac{\mathrm{kg\ CO_2e}}{kg\ N_2O} \times \frac{1\, t}{1000\, kg}$$

$$= -0.33\, t\ \mathrm{CO_2e\ ha^{-1}year^{-1}}$$

Where legume ratio correction factor is calculated by setting F_{legume} = 1 in Equation 2-1a and 2-1b; kg N_2O is converted to kg CO_2e using the global warming potential (GWP) of N_2O (298); kg C is converted to kg CO_2e using the conversion factor 44/12.

The FCS report set the baseline soil Cseq rate to 0.49 t C $ha^{-1}year^{-1}$ in the Pacific Maritime zone (Poeplau et al. 2015) and specific soil Cseq rates were determined by interpolation and extrapolation from different studies and expert opinions, and dependent on climate consideration and the characteristic of previous cash crop (Burton, McConkey, & MacLeod, 2021). Therefore, we used the uncertainty value reported by Poeplau et al. (2015) (± 87.25 %) as the uncertainty for RF_{Cseq} (Table A 13).

Uncertainty of $RF_{indirN2O}$ and RF_{dirN2O} are set to ±100% and ±34% (Table A 13), which are the uncertainties given in the NIR report for *Agriculture – Direct Agriculture Soils* (IPCC Emission Category 3.D.1) and *Agriculture – Indirect Agriculture Soils* (IPCC Emission Category 3.D.2) (Environment and Climate Change Canada, 2020), respectively.

Table A 13. *Reduction factors and uncertainties of cover crops effect on GHG emission.*

Previous cash crop	RF_{Cseq}	RF_{Cseq} Uncertainty	$RF_{indirN2O}$	$RF_{indirN2O}$ Uncertainty	RF_{dirN2O}	RF_{dirN2O} Uncertainty
	t CO_2e $ha^{-1}year^{-1}$	%	t CO_2e $ha^{-1}yr^{-1}$	%	t CO_2e $ha^{-1}yr^{-1}$	%
Winter cereal (wheat & rye)	-0.59	87.25%	-0.08	100%	-0.33	34%
Peas	-1.87	87.25%	-0.18	100%	-0.27	34%
Barley	-0.51	87.25%	-0.18	100%	-0.55	34%
Oats	-0.51	87.25%	-0.18	100%	-0.55	34%
Fallow replacement	-1.76	87.25%	-0.30	100%	-1.22	34%
Spring canola	-0.40	87.25%	-0.08	100%	-0.34	34%
Silage corn	-1.65	87.25%	-0.33	100%	-0.48	34%
Spring cereal (wheat & rye)	-0.40	87.25%	-0.08	100%	-0.34	34%
Potato	-0.95	87.25%	-0.40	100%	-0.60	34%
Field vegetables	-1.80	87.25%	0.07	400%	-0.09	122%

The total RF for planting cover crops is the sum of all three RFs for the major GHG emission pathways (Table A 14). The combined RF values are shown in Table A 14 and calculated following the equation:

$$RF_{combined} = RF_{Cseq} + RF_{indirN2O} + RF_{dirN2O}$$

For example, $RF_{combined}$ of winter cereal is calculated as:

$$RF_{combined} = RF_{Cseq} + RF_{indirN2O} + RF_{dirN} \quad = (-0.59) + (-0.08) + (-0.33) = -1\ t\ \mathrm{CO_2e\ ha^{-1}year^{-1}}$$

The combined uncertainty for RF total is calculated by combining uncertainties using Equation 1-3b**:**

$$Combined\ uncertainty = \frac{\sqrt{(activity\ 1 \times uncertainty\ of\ activity\ 1)^2 + (activity\ 2 \times uncertainty\ of\ activity\ 2)^2}}{|activity\ 1 + activity\ 2|}$$

$$= \frac{\sqrt{(-0.59 \times 87.25\%)^2 + (-0.08 \times 100\%)^2 + (-0.33 \times 34\%)^2}}{|(-0.59) + (-0.08) + (-0.33)|} = 53\%$$

5.4. Maximum GHG benefit potential

The maximum GHG benefit potential is calculated as:

$$Max.GHG\ benefit\ potential = reduction\ factor \times total\ activity\ units \times biophysical\ limit \times \frac{1\ kt}{1000\ t}$$

Using winter cereal as an example, the GHG benefit potential is calculated as:

$$Max.GHG\ benefit\ potential = reduction\ factor \times total\ activity\ units \times biophysical\ limit \times \frac{1\ kt}{1000\ t}$$

$$= -1\ t\ \mathrm{CO2e\ ha^{-1}year^{-1}} \times 12{,}900\ ha \times 90\% \times \frac{1\ kt}{1000\ t}$$

$$= -11.59\ kt\ \mathrm{year^{-1}\ CO_2e}$$

The combined maximum GHG benefit potential of adopting cover crops as a BMP for all the annual field crops selected in this analysis is also calculated (see total in Table A 14). The combined uncertainty for this total maximum GHG benefit potential is again calculated using the error propagation (Equation 1-3b).

Table A 14. *$RF_{Combined}$, combined uncertainty, and maximum potential GHG reduction.*

Previous cash crop	Crop seeded area	Max. adoption potential	RFCombined	RFCombined uncertainty	Max. GHG benefit potential
	ha	%	t CO_2e ha^{-1}year^{-1}	%	kt CO_2e
Winter cereal (wheat & rye)	12,900	90%	-1.00	53%	-11.59
Peas	26,300	95%	-2.31	71%	-57.82
Barley	29,900	85%	-1.24	42%	-31.60
Oats	29,100	85%	-1.24	42%	-30.76
Fallow replacement	19,100	100%	-3.28	49%	-62.64
Spring canola	37,300	75%	-0.82	46%	-22.87
Silage corn	15,800	85%	-2.46	60%	-33.04
Spring cereal (wheat & rye)	18,600	75%	-0.82	46%	-11.40
Potato	2,630	70%	-1.96	48%	-3.60
Field vegetables	5,058	80%	-1.82	79%	-7.36
Total	**196,688**	**93%**	**-1.49**	**22%**	**-272.69**

5.5. Cost of adoption

According to the FCS economics report (De Laporte, Schuurman, & Weersink, 2021), the estimated cost of implementing cover crops is CA$ 47.98 ha^{-1}year^{-1}.

5.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 15. *Summary of qualitative scoring for BMP: planting cover crops.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	3	Long term GHG benefits, but with decreased benefits over time	3	Uncertainty is low, based on expert, anecdotal evidence
MRV feasibility	2	The methods are developed but are costly, with high uncertainty and are not widely accepted	N/A	N/A

Soil quality	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	4	Uncertainty is low, based on concrete evidence
Water quality / conservation	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	4	Uncertainty is low, based on concrete evidence
Air quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	2	Uncertainty is low, based on non-expert judgement
Biodiversity / pest management	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	2	This co-benefit will not be impacted by this practice, and/or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Adaptation	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence

5.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *Hard to estimate adoption potential, but likely something around 35% across the whole province and all commodities, but could be higher in the organic sector.*
- *The uptake potential is large but will require in-field demonstrations of how it can work; for example: how to manage residue in the spring or how to incorporate the cover crop with either livestock or other methods that do not cause significant soil disturbance but still allow for successful seed bed preparation.*
- *For adoption potential, will need to consider that even for growers who intend to plant a cover crop, there will be variables that can't be controlled (i.e., weather, etc.) that will prevent cover crops from being planted every year, even if the intention is there.*
- *If the termination of the cover crop involves the use of herbicides or access of the land early in the year, there may be incidences where the co-benefit on biodiversity/pest management, water and soil quality will be cancelled out.*

- *Cost of adoption values seem accurate as presented for direct costs, but indirect costs should also be considered, such as not being able to get a second crop succession in, and reduced cash crop yield from needing to plant a cover crop, i.e. having to forgo potential yield and profit.*
- *Cover crops are an integral part to regenerative agriculture (keeping soil covered), however, in the NE where the majority of canola, wheat, and other cereals is grown, having cover crops in the non-growing season may not be feasible due to the shortness of the growing season. Instead, other compensation models should also be considered. For example: last year crop insurance had one of the largest payouts for crop losses in the NE (in the range of 14-16 mio dollars). If even a fraction of this compensation money would be made available to producers to allow them an economic way to grow a cover crop during the growing season (thereby foregoing the growth of a cash crop), we may be able to provide a soil health benefit greater than simply paying for lost crops with no improvement to soil health. It could be considered like health prevention (building soil health) rather than paying the health cost bill afterwards (crop loss compensation). If producers could receive sufficient financial coverage to make it economically meaningful to rotate fields out of production and into cover crops (possibly with the added livestock grazing agreement with a neighboring livestock producer) the addition of soil organic matter (and hence carbon sequestration) in addition to the well documented soil health benefit could provide synergistic benefits without necessarily spending additional financial resources when it is co-joined with crop insurance.*
- *This BMP could offer a large return on investment as the adoption of the practice would also offer soil health improvement benefits, especially when a diversity of cover crops are utilized. The benefit of soil health increase and the opportunity to reduce synthetic fertilizer input needs should be taken into account in terms of beneficial outcomes of this BMP.*

A.6. BMP: Manure composting

Manure management is a major source of direct N_2O and CH_4 emission in the agriculture sector, which accounts for 3846 kt CO_2e of the 2018 annual national GHG inventory (Environment and Climate Change Canada, 2020). Several studies suggest composting as an alternative manure storage method to reduce GHG emissions (Sommer et al. 2000, Amon et al. 2001, Hao et al. 2001); aerobic composting reduces the amount of CH_4 produced by anaerobic decomposition of organic matter. This BMP synopsis calculates the GHG reduction factor (RF) of manure composting and the maximum GHG benefit potential for implementing manure composting as a BMP in BC.

6.1. Total activity units

We used the total number of dairy cows and beef cows on feeding operation in BC from the published data of Statistics Canada (Statistics Canada, 2021).

6.2. Biophysical limit

The baseline adoption rate of manure composting is unknown. We used the same estimated manure accessibility for anaerobic digestion by Wang et al. (2020), 62.5% (±20%), as the biophysical limit for manure that are available for composting.

6.3. GHG reduction factor

Pattey et al. (2005) studied N_2O and CH_4 emissions from three types of manure storage methods (stockpile, slurry, and composting) for both beef cattle and dairy cattle during a 3-month period in the summer. The annual emission of direct N_2O and CH_4 found in this study are summarized in Table A 16.

Table A 16. *Annual GHG emission during storage of three different methods comparing to the emission factors of manure storage given by Table A6.4-6 of the NIR report (Environment and Climate Change Canada, 2020).*

	Dairy cattle		Beef cattle	
	CH_4 emission	N_2O emission	CH_4 emission	N_2O emission
	t CO_2e $hd^{-1}yr^{-1}$			
Slurry	1.30	0.07	0.36	0.01
Stockpile	0.42	0.27	0.07	0.01
Compost	0.08	0.39	0.003	0.05
NIR emission factor	0.95	0.27	0.11	0.33

The aerobic composting reduced CH_4 emissions and promoted the emission of N_2O as expected, but when the tradeoff between N_2O and CH_4 is taken into account, the net GHG emission is reduced relative to the NIR emission factor (EF) of cattle manure storage (shown in Table A 16). Therefore, the GHG reduction factor (RF) is calculated by subtracting the NIR EF with combined emission of N_2O and CH_4:

$$GHG\ RF\ of\ manure\ composting\ (t\ CO_2e\ 1000\ hd^{-1}year^{-1}) = \left(\left(Composting_{N_2O} + Composting_{CH_4}\right) - \left(EF_{N_2O} + EF_{CH_4}\right)\right) tCO_2ehd^{-1}year^{-1} \times 1000\ cattle$$

For dairy cattle:

$$GHG\ RF\ of\ manure\ composting = \left((0.39 + 0.08) - (0.27 + 0.95)\right) t\ CO_2e\ hd^{-1}year^{-1} \times 1000\ cattle = -751.46\ t\ CO_2e\ 1000\ hd^{-1}year^{-1}$$

For beef cattle:

$$GHG\ RF\ of\ manure\ composting = \left((0.05 + 0.003) - (0.33 + 0.11)\right) t\ CO_2e\ hd^{-1}year^{-1} \times 1000\ cattle = -361\ t\ CO_2e\ 1000\ hd^{-1}year^{-1}$$

Pattey et al. (2005) did not report any quantitative estimation of uncertainty. We instead used the emission factor uncertainties of direct N_2O and CH_4, 44% and 32%, respectively, given by the NIR report for manure management (IPCC emission source category 3.D.1) as the estimated uncertainty of direct N_2O and CH_4 emission from manure composting (Environment and Climate Change Canada, 2020). Uncertainties of these two gases are combined using Equation 1-3b to calculate the combined uncertainty of RF:

$$Uncertainty\ of\ RF = \frac{\sqrt{\left(EF_{N_2O} \times Uncertainty_{N_2O}\right)^2 + \left(EF_{CH_4} \times Uncertainty_{CH_4}\right)^2 + \left(Composting_{N_2O} \times Uncertainty_{N_2O}\right)^2 + \left(Composting_{CH_4} \times Uncertainty_{CH_4}\right)^2}}{\left|\left(Composting_{N_2O} + Composting_{CH_4}\right) - \left(EF_{N_2O} + EF_{CH_4}\right)\right|}$$

For dairy cattle:

$$Uncertainty\ of\ RF = \frac{\sqrt{(0.95 \times 44\%)^2 + (0.27 \times 32\%)^2 + (0.39 \times 44\%)^2 + (0.08 \times 32\%)^2}}{|0.39 + 0.08 - 0.95 - 0.27|} = 49\%$$

For beef cattle:

$$Uncertainty\ of\ RF = \frac{\sqrt{(0.33 \times 44\%)^2 + (0.11 \times 32\%)^2 + (0.05 \times 44\%)^2 + (0.003 \times 32\%)^2}}{|0.05 + 0.003 - 0.33 - 0.11|} = 42\%$$

6.4. Maximum GHG benefit potential

Maximum GHG benefit potential of manure composting is calculated as:

$$Max.GHG\ benefit\ of\ manure\ composting\ (t\ CO_2e\ year^{-1}) = RF\ (t\ CO_2e\ 1000\ hd^{-1}year^{-1}) \times total\ activity\ units\ (1000\ cattle) \times biophysical\ limit\ (\%) \times \frac{1\ kt}{1000\ t}$$

For dairy cattle:

$$Max.GHG\ benefit\ of\ manure\ composting\ (kt\ CO_2e\ year^{-1}) = -751.46\ (t\ CO_2e\ 1000\ hd^{-1}year^{-1}) \times 83.5\ (1000\ cattle) \times 62.5\% \times \frac{1\ kt}{1000\ t} = -39.53\ kt\ CO_2e\ year^{-1}$$

For beef cattle:

$$Max.GHG\ benefit\ of\ manure\ composting\ (kt\ CO_2e\ year^{-1}) = -361\ (t\ CO_2e\ 1000\ hd^{-1}year^{-1}) \times 26\ (1000\ cattle) \times 62.5\% \times \frac{1\ kt}{1000\ t} = -5.91 kt\ CO_2e\ year^{-1}$$

Uncertainty of the GHG benefit is calculated using Equation 0-3a**:**

$$Uncertainty\ of\ GHG\ benefit = \sqrt{Uncertainty_{activity}^2 + Uncertainty_{RF}^2}$$

For dairy cattle:

$$Uncertainty\ of\ GHG\ benefit = \sqrt{(62.5\%)^2 + (49\%)^2} = 53\%$$

For beef cattle:

$$Uncertainty\ of\ GHG\ benefit = \sqrt{(62.5\%)^2 + (42\%)^2} = 46\%$$

The combined max. GHG benefit of both dairy cattle and beef cattle, -45.44 kt CO_2e year^{-1}, equals to the sum of the max. GHG benefit of each livestock operation. The uncertainty of combined max. GHG benefit is calculated Equation 1-3b**:**

$$Uncertainty\ of\ combined\ GHG\ benefit$$

$$= \frac{\sqrt{\left(Benefit_{dairy} \times Uncertainty_{dairy}\right)^2 + \left(Benefit_{beef} \times Uncertainty_{beef}\right)^2}}{|Benefit_{dairy} + Benefit_{beef}|}$$

$$= \frac{\sqrt{(-39.53 \times 53\%)^2 + (-5.91 \times 46\%)^2}}{|-39.53 - 5.91|} = 47\%$$

6.5. Cost of adoption

Cost of manure composting varies a lot based on the type of facility, aeration methods, and the size of the farm. Cost can also be compensated by offsetting fertilizer purchase for crop production and selling finish product as compost/garden soil. The estimated cost in this synopsis is only the upfront investment of building a composting facility. According to O2Compst, a compost solution contractor in Washington State, US, the cost of building a self-funded moderate cost composting facility that has a lifespan of 15-25 years and volume of 25 cubic yard is US$ 15,000. Adoption cost per year by 2030 is calculated as

$$Cost\ of\ manure\ composting\ (CA\$\ year^{-1}) = \frac{composting\ facility\ cost\ (US\$)}{8\ years} \times \frac{CA\$\ 1}{US\$\ 0.7}$$

$$= \frac{US\$15{,}000}{8\ years} \times \frac{CA\$\ 1}{US\$\ 0.7} = \text{CA\$2,678.6}\ year^{-1}$$

6.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 17. *Summary of qualitative scoring for BMP: Manure composting.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	4	Long-term GHG benefits, no decrease in benefits over time	3	Uncertainty is low, based on expert, anecdotal evidence
MRV feasibility	1	There has been some methods development	N/A	N/A
Soil quality	3	This co-benefit will be increased by this practice, or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Water quality / conservation	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Air quality	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	2	Uncertainty is low, based on non-expert judgement
Biodiversity / pest management	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	4	Uncertainty is low, based on concrete evidence
Financial risks / benefits	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Adaptation	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	2	Uncertainty is low, based on non-expert judgement
Regulation barriers	4	Requires no approval, or requires a simple permit	3	Uncertainty is low, based on expert, anecdotal evidence

6.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *Adoption potential for this BMP (for confined beef and for confined dairy (only solid manure) would likely be 20%, unless there are substantial incentives*
- *Adoption could be increased if the compost end-product is also seen as valuable. Well produced compost could be beneficial in vegetable production, in home gardens and producers seeking to reduce synthetic fertilizer inputs. Again, more awareness and education would be needed.*
- *Consider whether emission rates are consistent season to season (i.e., are they impacted by sunshine, air temperature, humidity, rain and other environmental factors?)*
- *Would be useful if the denominator of the data were more clear – i.e. per tonne of compost produced?*
- *Cost of adoption should include consideration of a bulking agent which is not currently considered, and sourcing this type of material will also be a hinderance to adoption rates. Currently, the proposed cost would pay for a three-bay system (~2,500 cubic yards), but likely a more costly system would be required to actually provide substantial emission reductions through control of environmental variables in the composting process.*
- *[Note, this feedback has been incorporated in the updated qualitative scoring, but is included here for the description provided]: Compared to status quo, long-term benefit is probably more 3. As for the feasibility, I think measuring emissions is actually easier as we have confined system. I would give it a 2 or 3. If we include the application of the compost to the land (rather than the non-composted material), I would give higher ratings for water quality and biodiversity (in particular pest management). As for the regulatory barriers - a larger compost operation may encounter odour and thus some local resistance.*
- *Composting of manure from winter facilitates (i.e., from cow calf operations which are grazing in the summer) could be feasible, but it is likely better practice to encourage extensive feeding options (such as bale grazing, swath grazing, and fall or winter grazing*

of cover crops) to reduce the days spent in a drylot to reduce the manure accumulated. Extensive feeding options would bring a greater benefit to soil health, soil fertility and reduce yardage cost for cattle producers. Extensive feeding is a long established practice that would benefit from more widespread adoption and fit with the principles of regenerative agriculture (incorporating livestock). Education and training may be necessary on how run electric fencing in winter months, how much feed to allocated during winter weather and providing financial support for things like portable wind shelters to make grazing on open cash crop fields possible.

A.7. BMP: Nitrification inhibitor (DCD)

Nitrification inhibitor (NI) is a group of fertilizer additives that suppress the nitrification process in soil to prevent the conversion from ammonium-N (NH_4-N) to nitrate-N (NO_3-N) and reduce direct N_2O emissions. This BMP synopsis calculates the GHG benefit potential for one type of nitrification inhibitor, dicyandiamide (DCD, $C_2H_4N_4$), for field crop production in BC.

7.1. Total activity units

See total activity units for BMP: 4R nutrient management.

7.2. Biophysical limit

Use of nitrification inhibitor is suggested by the FCS GHG quantification report (Burton, McConkey, & MacLeod, 2021) as part of the Intermediate and Advanced 4R nutrient management practices, which has an estimated baseline adoption rate of 30% in 2017. Thus, we assumed the biophysical limit of implementing DCD is 70% for all selected crops.

7.3. GHG reduction factor

Gilsanz et al. (2016) conducted a meta-analysis with 111 datasets from 39 studies on the effect of NI, specifically DCD, on GHG emissions when applied to cropland with fertilizers. From this meta-analysis, DCD is reported to reduce direct N_2O emissions from soil by 34.3% ± 13%.

Therefore, using our previous calculations of direct N_2O emissions for the 4R nutrient management BMP (Table A 1), we calculated the GHG reduction factor (shown in Table A 18) as:

$$GHG\ reduction\ factor\ (RF, t\ CO_2e\ ha^{-1}year^{-1})$$
$$= direct\ N_2O\ emission\ from\ soil\ (kg\ CO_2e\ ha^{-1}year^{-1})$$
$$\times N_2O\ reduction\ effect\ of\ DCD \times (-1) \times \frac{1\ t}{1000\ kg}$$

Taking wheat again as the example, the RF of using DI with an N fertilizer for wheat is calculated as:

$$GHG\ reduction\ factor\ (\ t\ CO_2e\ ha^{-1}year^{-1})$$
$$= 358\ kg\ CO_2e\ ha^{-1}year^{-1} \times 34.3\ \% \times (-1) \times \frac{1\ t}{1000\ kg}$$
$$= -0.12\ t\ CO_2e\ ha^{-1}year^{-1}$$

The RF uncertainty is calculated by combining uncertainties using Equation 0-3a**:**

$$Uncertainty\ of\ wheat\ RF$$
$$= \sqrt{(uncertainty\ of\ N\ rate)^2 + (uncertainty\ of\ direct\ N_2O\ EF)^2 + (uncertainty\ of\ N_2O\ reduction\ effect)^2}$$
$$= \sqrt{(10\%)^2 + (27\%)^2 + (13\%)^2} = 32\%$$

Table A 18. *GHG reduction factor and uncertainty of DCD for selected filed crops in BC.*

Crop	**Direct N_2O emission**	**N_2O emission reduction effect**	**N_2O emission reduction effect uncertainty**	**GHG reduction factor**	**RF uncertainty**
	kg CO_2e ha^{-1} yr^{-1}		%	t CO_2e ha^{-1} yr^{-1}	%
Wheat (spring & winter)	358	34%	13%	-0.12	32%
Canola	477	34%	13%	-0.16	31%
Corn (silage & grain)	653	34%	13%	-0.22	32%
Potato	381	34%	13%	-0.13	36%
Oats	348	34%	13%	-0.12	32%
Barley	251	34%	13%	-0.09	32%
Peas (dry)	191	34%	13%	-0.07	32%
Grapes	162	34%	13%	-0.06	32%
Berries	238	34%	13%	-0.08	32%
Other tree fruits	477	34%	13%	-0.16	32%
Field vegetables	453	34%	13%	-0.16	32%

7.4. Maximum GHG benefit potential

Using the same steps and equations as 4R, the GHG benefit and combined GHG benefit of applying DCD are calculated and tabulated in Table A 19.

Table A 19. *GHG benefit of applying DCD for selected field crops in BC.*

Crop	Total activity units	Biophysical limit	GHG reduction factor (RF)	GHG benefit	GHG benefit uncertainty
	ha	%	t CO_2e ha^{-1} yr^{-1}	kt CO_2e yr^{-1}	%
Wheat (spring & winter)	27,500	70%	-0.12	-2.36	32%
Canola	37,300	70%	-0.16	-4.27	31%
Corn (silage & grain)	16,600	70%	-0.22	-2.6	32%
Potato	2,630	70%	-0.13	-0.24	36%
Oats	29,100	70%	-0.12	-2.43	32%
Barley	29,900	70%	-0.09	-1.80	32%
Peas (dry)	26,300	70%	-0.07	-1.20	32%
Grapes	3,974	70%	-0.06	-0.15	32%
Berries	14,128	70%	-0.08	-0.81	32%
Other tree fruits	6,975	70%	-0.16	-0.80	32%
Field vegetables	5,058	70%	-0.16	-0.55	32%
All crops combined	199,465	70%	-0.12	-17	12%

7.5. Cost of adoption

Although it is difficult to obtain the price of commercial DCD product, e.g. *SuperU* and *Agrotain*, we found the price for importing granular DCD in bulk from China is approximately US$ 2.5 kg^{-1}. The recommended application rate of DCD is 10 kg ha^{-1} such that the cost of adoption of DCD can be roughly estimated as:

$$Cost\ of\ adoption\ of\ DCD$$
$$= Unit\ price\ of\ DCD(US\$\ kg^{-1}) \times currency\ exchange\ rate \left(\frac{CA\$\ 1}{US\$\ 0.7}\right) \times application\ rate(kg\ ha^{-1}) = 2.5\ US\$\ kg^{-1} \times \frac{CA\$\ 1}{US\$\ 0.7} \times 10\ kg\ ha^{-1} = CA\$\ 35.7\ ha^{-1}$$

7.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 20. *Summary of qualitative scoring for BMP: DCD nitrification inhibitor.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	3	Possibility for some net GHG emissions in long term	3	Uncertainty is low, based on expert, anecdotal evidence
MRV feasibility	1	There has been some methods development	N/A	N/A
Soil quality	2	This co-benefit will not be impacted by this practice, and/or harms and benefits offset	2	Uncertainty is low, based on non-expert judgement
Water quality / conservation	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Air quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms.	1	Uncertainty is high
Biodiversity / pest management	2	This co-benefit will not be impacted by this practice, and/or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	2	This co-benefit will not be impacted by this practice, and/or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence

Adaptation	2	This co-benefit will not be impacted by this practice, and/or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Regulation barriers	4	Requires no approval, or requires a simple permit	3	Uncertainty is low, based on expert, anecdotal evidence

7.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following points based on feedback collected from AFF agrologists:

- *Why is there consideration to provide a payment to use nitrification inhibitors as this could qualify as normal farm practice? In the past, when it has been proposed that producers could get financial support to apply lime (to increase pH levels and thereby increasing the availability of fertilizer, i.e. reduce fertilizer lost to the environment), the argument was made that this would be a normal farm practice and would not qualify for a BMP. If nitrification inhibitors are supported with BMP funding, there should also be an opportunity for growers to receive support for lime applications to ameliorate soil pH as this would also reduce nitrogen loss to the environment.*

A.8. BMP: Planting woody perennials as vegetative buffers

Woody perennials, (i.e. trees and shrubs) can mitigate GHG emissions by incorporating and storing atmospheric carbon dioxide (CO_2) through photosynthesis as carbon (C) in woody biomass and by contributing organic material to store C as soil organic carbon. As trees and shrubs grow, the C sequestration (Cseq) rate increases for a time and then begins to taper off until they are mature and reach a steady state where the C remains stored until they die or are cut down. Here we provide details for calculating the GHG benefit potential (combined reduction of emissions and Cseq) for planting woody perennials as vegetative buffers on cropland.

The emissions associated with this BMP fall under the National GHG Inventory Report (NIR) category of land-use, land-use change, and forest (LULUCF). The GHG benefit potential for planting woody perennials is calculated based on the Cseq rates in aboveground biomass and changes in soil organic carbon (SOC) (t C ha^{-1} $year^{-1}$).

Woody perennials (trees and shrubs) planted in vegetative buffers at farm field edges, also known as shelterbelts and windbreaks, have been shown to provide sizeable GHG benefits (Thiel et. al 2015; Rallings et al. 2019; Rallings et al. 2020) and a number of co-benefits including to improve pollinator habitat (Pasher et al. 2016), reduce soil erosion (García-Feced et al. 2014), moderate microclimate (Wiseman et al. 2009), and reduce nutrients and pollutants losses to neighboring waterways (García-Feced et al. 2014).

8.1. Total activity units

To estimate the total area available for planting vegetative buffers on BC cropland, we estimated the total length of farm perimeters that are not yet planted with vegetative buffers. For this estimate, we first narrowed down the types of cropland that are applicable. Based on the Census of Agriculture published by Statistics Canada (Statistics Canada, 2021a), land in crops include annual field crops (e.g., grains, oilseed, potatoes, and corn), fruit trees, field vegetables, hay, and summer fallow. We excluded Christmas trees and natural pastures. Data for the total land area in crops and for the total number of farms for which they were reported were then extracted to calculate the average cropland area of a single farm in BC:

$$Avg.\ cropland\ area\ (ha) = \frac{Total\ cropland\ area\ (ha)}{Total\ number\ of\ farms\ reported}$$

$$= \frac{580{,}820\ ha}{13{,}258\ farm}$$

$$= 43.81\ ha\ farm^{-1}$$

We assumed that vegetative buffers can be planted along the perimeter of all cropland and that the average cropland is in the shape of a square. The length of this average cropland perimeter was thus calculated as:

$$Avg.\,cropland\ perimeter\ (m)$$
$$= \left(\sqrt{avg.\,cropland\ area\ (ha) \times squaremeter\ conversion}\right) \times 4\ sides$$

$$= \left(\sqrt{43.81\ ha\ farm^{-1} \times 10{,}000\ m^2\ ha^{-1}}\right) \times 4$$

$$= 2{,}647.54\ m\ farm^{-1}$$

We also assumed that the width of a vegetative buffers is 6 meters based on observations reported in Rallings et al. (2019) and that neighboring cropland share the same hedgerow (i.e. 3 meters for each side), thus the total area of vegetative buffers is calculated as:

$$Total\ hedgerow\ area\ (ha)$$
$$= avg.\,cropland\ perimeter \times width\ of\ hedgerows\ on\ one\ side$$
$$\times total\ number\ of\ farms \times hectare\ conversion\ \left(\frac{ha}{m^2}\right)$$

$$= 2{,}647.54\ m\ farm^{-1} \times 3\ m \times 13{,}258\ farms \times \frac{1\ ha}{10{,}000\ m^2}$$

$$= 10{,}530.31\ ha$$

There were no uncertainty estimates reported from Statistics Canada that could be associated with this calculation.

8.2. Biophysical limit

According to Statistics Canada (Statistics Canada, 2021b), 5% of farms in BC have existing field shelterbelts or windbreaks. We thus assumed that 95% of farms in BC do *not* have existing vegetative buffers. There was no uncertainty provided with this number by Statistics Canada, but a qualitative description as “acceptable quality”.

8.3. GHG reduction factor

Based on results from studies conducted in Canada and the U.S., we estimated that the aboveground Cseq rate of planting woody perennials as vegetative buffers on cropland is 4.02 (± 60%) t C ha^{-1} $year^{-1}$ (mean ± CV). The uncertainty associated with this value is calculated as the coefficient of variation (CV; %) associated with the range of mean values recorded from the literature which captured a range of vegetative buffers type, species composition and age (*Table A 21*).

Table A 21. *Vegetative buffers above-ground C stock, age of stand and Cseq rate of selected studies.*

Source	Aboveground C stock	Age of stand	Aboveground Cseq rate
	t C ha^{-1}	years	t C ha^{-1} yr^{-1}
Dowell (2020)	120	30	4.00
Zhou et al. (2007)	-	60	9.10
Possu et al. (2016)	-	50	2.45
Possu et al. (2016)	-	50	4.39
Amadi et al. (2016)	253.26	60	4.22
Amadi et al. (2016)	162.24	60	2.70
Amadi et al. (2016)	49.56	60	0.83
Arevalo et al. (2009)	-	9	4.50
Mean	**117.01**	**47.38**	**4.02**
CV%	73%	39%	60%

We calculated the Cseq rate of SOC under vegetative buffers from the mean (and propagated uncertainty) of two studies: one conducted in southwest BC and the other in Saskatchewan (Table A 22). Thiel et al. (2015) reported 1.34 (± 56%) t C ha^{-1} $year^{-1}$ greater soil C sequestered under planted vegetative buffers compare to adjacent annual cropland using bulk density estimates to 30 cm in Delta, BC. Dhillon and Van Rees (2016) reported 0.69 t C ha^{-1} $year^{-1}$ (±54%) more soil C than adjacent agricultural fields in the top 0 - 30 cm. Thus, the calculated average change in soil C relative to adjacent agricultural land is 1.02 (± 41%) t C ha^{-1} $year^{-1}$.

Table A 22. *Hedgerow soil C stock (0-30 cm), age of stand, and soil Cseq rate of selected studies.*

	Agriculture field		**Vegetative buffers**				**Stand**		**Vegetative buffers**	**Combined uncertainty**
Source	**Soil C stock**	**Soil C uncertainty**	**Soil C stock**	**Soil C uncertainty**	**Increased soil C**	**Increased soil C uncertainty**	**Age**	**Age uncertainty**	**Soil C increase per year**	
	t C ha^{-1}	%	t C ha^{-1}	%	t C ha^{-1}		years		C ha^{-1} yr^{-1}	%
Thiel et al. (2015)	64.7	8%	83.15	7%	18.45	43%	14	36%	1.34	56%
Dhillon & Van Rees (2016)	71.9	27%	89.0	27%	17.15	49%	25	23%	0.69	54%
Mean	68.29	14%	86.09	14%	17.80	32%	19	20%	1.02	41%

Combined Cseq rate of planting woody perennials as vegetative buffers is calculated as the sum of Cseq by both aboveground biomass and SOC:

$$Combined\ \ Cseq\ rate\ of\ hedgerows = \Delta\ aboveground\ biomass\ C + \Delta\ SOC$$

$$= 4.02\ t\ C\ ha^{-1}\ year^{-1} + 1.02\ t\ C\ ha^{-1} year^{-1}$$

$$=5.04\ \text{t C ha}^{-1}\ \text{year}^{-1}$$

Uncertainties are combined using Equation 1-3b**:**

$$Combined\ uncertainty\ of\ total\ Cseq$$

$$= \frac{\sqrt{(\Delta\ aboveground\ C \times uncertainty)^2 + (\Delta\ SOC \times uncertainty)^2}}{combined\ Cseq}$$

$$= \frac{\sqrt{(4.02 \times 60\%)^2 + (1.02 \times 41\%)^2}}{5.04} = 49\%$$

The GHG RF of planting woody perennials as vegetative buffers on cropland is calculated as:

$$Reduction\ factor$$
$$= total\ Cseq \times CO_2\ conversion\ factor \times\ negative\ emission\ reduction\ modifier$$
$$= 5.02\ \ t\ C\ ha^{-1}year^{-1} \times \frac{44\ g\ CO2}{12\ g\ C} \times (-1)$$
$$= -18.48\ t\ CO_2e\ \ ha^{-1}year^{-1}$$

8.4. Maximum GHG benefit potential

Based on the calculations above, the provincial maximum GHG benefit potential was calculated using **Equation 1-1** as:

$$Max.GHG\ benefit\ potential$$
$$= reduction\ factor \times total\ activity\ units \times biophysical\ limit$$
$$= -18.48\ kt\ CO_2e\ \ ha^{-1}\ year^{-1} \times 10530.31\ ha \times 95\%$$
$$= -184.87\ kt\ CO_2e\ \ year^{-1}$$

As the total potential area for planting vegetative buffers relied on many assumptions and had no associated uncertainty, and the area already planted to vegetative buffers also had no associated uncertainty, we estimated that the uncertainty associated with vegetative buffers area was 100%. Thus, the combined uncertainty of max. GHG benefit potential is calculated by Equation 0-3a:

$$Combined\ uncertainty\ of\ max.potential\ GHG\ reduction$$
$$= \sqrt{(uncertainty\ of\ RF)^2 + (uncertainty\ of\ activity\ data)^2}$$
$$= \sqrt{0.49^2 + 1^2}$$
$$= 111\%$$

8.5. Cost of adoption

The cost of adoption for planting vegetative buffers was determined based on the estimated planting costs alone divided by the 8 years from 2022 to 2030. These costs do not account for maintenance or the total life span of the vegetative buffers which may live past 60 years. Applying a discount rate over a more accurate lifespan of the vegetative buffers would likely reduce the overall costs substantially. Morandin et al. (2016) reported a cost of planting vegetative buffers of USD$ 400 300 m^{-1} in California

Vegetative buffers cost (per hectare per year) in BC is then calculated as:

$$Cost\ of\ planting\ one\ hectare\ of\ hedgerows\ or\ riparian\ buffers\ in\ BC = \frac{US\$}{1\ m\ hedgerow} \times currency\ exchange\ rate \times \frac{1\ ha}{width\ of\ hedgerow} \times \frac{1}{8\ years} = \frac{US\$\ 1.3}{m} \times \frac{CA\$\ 1}{US\$\ 0.7} \times \frac{10000\ m^2}{6\ m} \times \frac{1}{8\ years} = CA\$\ 435.28\ ha^{-1}year^{-1}$$

8.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 23. *Summary of qualitative scoring for BMP: Plant woody perennials (as vegetative buffers or riparian buffers).*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	3	Long-term GHG benefits, but with decreased benefits over time	3	Uncertainty is low, based on expert, anecdotal evidence
MRV feasibility	2	The methods are developed but are costly, with high uncertainty and are not widely accepted	N/A	N/A
Soil quality	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence

Water quality / conservation	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Air quality	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Biodiversity / pest management	3	This co-benefit will be increased by this practice and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Adaptation	3	This co-benefit will be increased by this practice and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence

8.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *The crop loss resultant from the change in use from crop to vegetative buffers, and the cost of farmland (exceeds $120K/acre in lower mainland) have not been considered. These are significant costs.*
- *Adoption potential across all farms is likely 30-40%, but may be higher in the organic sector given that organic farms need to have a buffer anyways (although these farms also might already have a buffer planted).*
- *Adoption rates of vegetative buffers are generally very low, particularly amongst berry producers where there are concerns with harboring pests such as SWD. The largest uptake seems to be for poultry producers wanting to minimize effects on neighbors by capturing dust particles from fans. Vegetative buffers are also installed due to complaints in most cases, not as a choice by the landowner. Uptake is likely ~ 15%.*
- *Likely low adoption of this practice as there is the real or perceived disadvantage of maneuvering fields with large equipment when there are trees in the way. Additionally, hedgerows are considered high water users which creates an edge effect on the adjacent*

crop. When moisture is already a limiting factor, it may be challenging to convince producers to plant trees which may create additional competition for a limiting resource.

- *It is possible that all cropland could be planted, but it isn't always appropriate. Airflow modelling has demonstrated that there are places where vegetative buffers are effective and places where they can cause detrimental effects with downwash of particulates onto neighboring crops. Also, the potential for shading of hedgerows onto crops is a genuine concern and need to be planned accordingly.*
- *For the qualitative scoring, vegetative buffers don't necessarily contribute to enhanced water quality or conservation. It depends on how they are designed and the reasons for installation. I think this should be lowered to a 3. Similar concerns with air quality: the vegetative buffer may capture dust and pesticide drift, but these are large particulates that don't stay suspended in air very long; I would reduce this one to 3 as well.*
- *The assumption in 10.1 that average cropland is in the shape of a square may be limiting, while it is understood this approach would be used in analysis a caveat may be needed. Hedgerows (and shelterbelts) may have greater strategic applicability (in terms of co-benefits) in certain areas of farms over others which may in turn relate more to odds of adoption. In terms of available locations, existing infrastructure and field size may also be factors, as limitation may exist in terms of relocation costs, equipment size, etc.*
- *Regarding qualitative scoring: hedgerows, riparian buffers, and shelterbelts have been shown to have tangible production benefits, while it is understood that these are considered co-benefits in this analysis it may be beneficial to promote these benefits to potential adopters rather than simply as GHG reduction factor. Partial adoption, eg. use of plantings in some areas will be more likely than implementation across all available locations on a farm.*
- *Consider estimating the opportunity cost of this BMP: to improve applicability of information to potential end users (adopters) can cost of adoption be represented in a cost per km or m rather than ha?*
- *If considering riparian plantings, you may need to consider a regulatory category depending on if any works in/about a stream would be required as this would introduce another step.*
- *Planting trees and hedgerows may be beneficial in certain high-wind areas.*

- *Why was the planting of perennial forage cover not considered instead of tree cover? Although tree provide the visual impact of carbon being sequestered, the scientific literature points to perennial forage systems, especially native perennial forage systems as far superior in total carbon sequestration. Protecting and increasing the area of perennial grasslands should be a high priority and would likely have a larger adoption rate than planting hedgerows. Other provinces have histories of programs in support of perennial forage planting programs which could easily be adopted for BC and would be highly applicable in the Interior and Northern areas of the province*

A.9. BMP: Planting woody perennials as riparian buffers

Woody perennials, (i.e. trees and shrubs) can mitigate GHG emissions by incorporating and storing atmospheric carbon dioxide (CO_2) through photosynthesis as carbon (C) in woody biomass and by contributing organic material to store C as soil organic carbon. As trees and shrubs grow, the C sequestration (Cseq) rate increases for a time and then begins to taper off until they are mature and reach a steady state where the C remains stored until they die or are cut down. Here we provide details for calculating the GHG benefit potential (combined reduction of emissions and Cseq) for planting woody perennials as vegetative buffers on cropland.

The emissions associated with this BMP fall under the National GHG Inventory Report (NIR) category of land-use, land-use change, and forest (LULUCF). The GHG benefit potential for planting woody perennials is calculated based on the Cseq rates in aboveground biomass and changes in soil organic carbon (SOC) (t C ha^{-1} $year^{-1}$).

Planting trees and shrubs along agricultural lands adjacent to waterways as riparian buffers have shown to sequester large quantities of C in biomass and SOC (Dowell 2020). Riparian buffers provide a number of co-benefits, many similar to vegetative buffers, and additional benefits to water quality by shading waterways and protecting stream banks from erosion.

9.1. Total activity units

Total potential area for planting riparian buffers on BC agriculture land is unknown. In order to estimate this potential, we first downloaded GIS data from the BC Freshwater Atlas (Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2021a), BC Agricultural Land Reserve (BC ALR) (Provincial Agricultural Land Commission, 2021), and Range Pastures of BC (Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2021b). The lengths of all rivers found within the ALR were first categorized by either privately owned or Crown land and then summed to determine potential riparian buffer area for cropland. To determine riparian buffers for pasture, the sum of the lengths of all rivers found within the pastureland boundaries of private and Crown land was used. Based on provincial legislation for riparian areas and recommendations from the literature we determined the width of one side of the riparian buffer to be 30 m for primary streams (Schultz and Isenhart 1997, Fischer and Fischenich 2000, Mayer et al. 2007, Bentrup 2008), 20 m for secondary streams, and 10 m for tertiary streams. Upon further discussion with local experts, we adjusted the buffer widths to 10 m for primary streams, 5 m for secondary streams, and 0 m for tertiary streams (GEI Consultants, Inc., 2005). We then calculated the total area of riparian buffer by multiplying the buffer width by the length of the stream and multiplying by two to account for both sides of the stream (Table A 24). These values had no associated uncertainty.

Table A 24. Estimated riparian buffer area within boundaries of agricultural land reserve (ALR) and pasture land in BC

Stream type	1-side buffer width	Crown				Private			
		Cropland (ALR)		Pasture		Cropland (ALR)		Pasture	
		Length	Buffer area	Length	Buffer area	Length	Buffer area	Length	Buffer area
	m	m	ha	m	ha	m	ha	m	ha
Primary	10	3,596,672	7,193	5,491,091	10,982	3,256,177	6,512	8,216,982	16,434
Secondary	5	272,833	273	759,218	759	380,904	381	1,743,503	1,744
Tertiary	0	959,684	-	3,237,648	-	1,303,083	-	5,797,411	-
Total		4,829,189	7,466	9,487,957	11,741	4,940,164	6,893	15,757,896	18,177

9.2. Biophysical limit

We found no data on the current extent of land available for buffers outside of the analysis of the lower Fraser River Valley by Rallings et al (2020) and Dowell (2020). Through consultation with AFF agrologists we assumed that only 25% of the area available for planting buffers is actually suitable. Uncertainty of this value is unknown.

9.3. GHG reduction factor

One BC study in the Fraser Valley estimated that woody perennials in riparian buffers sequester 3.85 (±0.93) t C ha^{-1} $year^{-1}$ (mean +/- standard error) in aboveground biomass (Dowell, 2020). Based on the assumption that riparian buffers sequester CO_2 at the same rate as vegetative buffers compared to croplands, we used the same SOC Cseq rates used for the BMP: 'planting perennials as vegetative buffers'

Combined Cseq rate of planting woody perennials as riparian buffer on cropland was then calculated as the sum of Cseq by both aboveground biomass and SOC:

$Combined\ \ C\ sequstration\ rate\ of\ riparian\ buffer$

$$= aboveground\ biomass\ Cseq + \Delta\ SOC$$

$$= 3.85\ t\ C\ ha^{-1}year^{-1} + 1.02\ t\ C\ ha^{-1}year^{-1}$$

$$= 4.87\ t\ C\ ha^{-1}year^{-1}$$

Uncertainties are combined using Equation 1-3b as:

$Combined\ uncertainty\ of\ total\ C\ sequestration$

$$= \frac{\sqrt{(\Delta\ aboveground\ C \times uncertainty)^2 + (\Delta\ SOC \times uncertainty)^2}}{combined\ C\ sequestration}$$

$$= \frac{\sqrt{(3.85\ t\ C\ ha^{-1}year^{-1} \times 24\%)^2 + (1.02t\ C\ ha^{-1}year^{-1} \times 41\%)^2}}{4.87\ t\ C\ ha^{-1}year^{-1}}$$

$$= 21\%$$

The GHG RF of planting woody perennials as riparian buffer on ALR was calculated as:

$$RF = total\ C\ sequestration \times CO_2\,e\ conversion\ factor$$
$$\times\ negative\ emission\ reduction\ modifier$$

$$= 4.87\ t\ C\ ha^{-1}year^{-1} \times \frac{44\ g\ CO_2}{12\ g\ C} \times (-1) = -17.85\ t\ CO_2e\ \ ha^{-1}year^{-1}$$

For riparian buffers in pasture areas we assumed that there would be no difference in SOC values (McConkey et al. 2014, Environment and Climate Change Canada 2020). Thus, the GHG RF of planting woody perennials as riparian buffer on pasture is calculated as,

$$RF = total\ C\ sequestration \times CO_2\,e\ conversion\ facto$$
$$\times\ negative\ emission\ reduction\ modifier$$
$$= 3.85\ t\ C\ ha^{-1}year^{-1} \times \frac{44\ g\ CO_2}{12\ g\ C} \times (-1)$$
$$= -14.11\ t\ CO_2e\ \ ha^{-1}year^{-1} \pm 24\%$$

9.4. Maximum GHG benefit potential

We calculated the maximum GHG benefit potential using Equation 1-1 as:

$$Max. GHG\ benefit\ potential\ for\ cropland$$
$$= reduction\ factor \times total\ activity\ units \times biophysical\ limit$$
$$= -17.85\ t\ \ CO_2e\ \ ha^{-1}\ year^{-1} \times (6{,}893 + 7{,}466)\ ha \times 25\% +$$
$$= -64.09\ kt\ CO_2e\ \ year^{-1}$$

$$Max. GHG\ benefit\ potential\ for\ pasture$$
$$= -14.11 \times (18{,}177 + 11{,}741) \times 25\%$$
$$= -105.52\ kt\ CO_2e\ \ year^{-1}$$

Given the lack of uncertainty associated with the activity data and biophysical limits, similar to the vegetative buffers area, we also give the estimated riparian buffer area 100% uncertainty. Using Equation 0-3a we calculated combined uncertainty as:

$$Combined\ uncertainty\ of\ Max. potential\ GHG\ reduction$$
$$= \sqrt{(uncertainty\ of\ RF)^2 + (uncertainty\ of\ activity\ data)^2}$$

For cropland,

$$Combined\ uncertainty\ of\ Max. potential\ GHG\ reduction = \sqrt{0.21^2 + 1^2}$$
$$= 102\%$$

For pasture,

$$Combined\ uncertainty\ of\ Max. potential\ GHG\ reduction = \sqrt{0.24^2 + 1^2}$$
$$= 103\%$$

9.5. Cost of adoption

See Cost of Adoption for BMP: ‘Plant woody perennials as vegetative buffers’.

9.6. Qualitative scores

See Qualitative Scoring for BMP: ‘Plant woody perennials as vegetative buffers’.

9.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following points based on feedback collected from AFF agrologists:

- *Was pasture land the only crop type used for measuring riparian buffer potential? Was forage delineated from pasture? How do primary, secondary, and tertiary streams fit into stream classification systems in BC (S1-S6)? The Department of Fisheries and Oceans (DFO) would argue that 30 m is necessary, but that is not operationally possible on most agricultural landscapes, nor is it necessary to provide the functions that a stream requires. In managed systems, assessment methods such as the Riparian Areas Protection Regulation (RAPR) are not appropriate, but even the detailed assessment that the RAPR uses takes into consideration the specific needs of each stream individually. Generally, the buffer distance in that system is roughly 3x the channel width of the stream. A more effective means of assessing a stream is determining the proper functioning condition, which is not something the RAPR looks for. This is particularly important on managed landscapes where the riparian area may be small and limited, but the condition of the stream is still highly functional and providing the habitat and support for fish presence.*
- *For adoption potential, 50% would be something to strive for with the hope that you could recruit more. We are looking at roughly 350ha per year of planting for both the EFP/BMP program and Farmland Advantage, which are very conservative estimates, but it provides some context.*
- *Riparian buffers have been a long standing BMP and I would assume that anybody who intended on establishing riparian buffers would have already done so. There may be some uptake from new producers.*
- *For qualitative scoring, the contribution to water quality would be higher here than for hedgerows. I would put that value as a 4 here and a 3 for hedgerows. Also, biodiversity co-benefits would be higher for riparian buffers at a 4.*
- *Section 11.1 references Range Pastures of BC, this may have implications to regulatory section in regard to plantings on Crown Land.*
- *Recognizing that not all types/stages of riparian areas are dominated by woody vegetation how would appropriateness of BMP to site be assessed and incorporated into availability?*

- *Consider breaking this BMP into several categories – it may be possible to get different uptake of different width buffers; also working buffers vs set aside buffers could see different levels of uptake.*
- *Has the potential for working buffers been considered in cost eg. where florals, berries, or other sustainably harvested products are incorporated in long term buffer management?*
- *Recommend inclusion of data on opportunity cost of 10, 20, 30m buffers in this section both in terms of food supply and farm returns.*

A.10. BMP: Preserve existing forest from being converted to cropland

The emissions associated with this BMP fall under the National GHG Inventory Report (NIR) category of land-use, land-use change, and forest (LULUCF). The reduction factor (RF) for preserving forest from conversion is calculated from the avoided immediate CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions which are associated with logging, uprooting, and burning of biomass when forests are converted to cropland.

Each year in BC, deforestation and conversion to cropland causes immediate GHG emission from the loss of C stored in woody biomass and soil with residual emissions from soil lasting many years after the deforestation. If these forest lands are preserved from being converted to cropland, the prevented GHG emission could be counted as emission reduction. Environment and Climate Change Canada (ECCC) produce annual data for forestland-to-cropland (FL-CL) conversion rate (ha^{-1} $year^{-1}$) and the immediate emission caused by FL-CL conversion (kt CO_2e ha^{-1}) since 1990.

10.1. Total activity units

Assuming the FL-CL conversion rate stays the same as the last five years until 2030, the total forest area that can be preserved every year is calculated as:

$$Max. forest\ area\ preserved\ until\ 2030 = annual\ mean\ of\ FLCL\ conversion\ area$$

$$= 1{,}980\ \text{ha}$$

There was no reported uncertainty associated with the maximum area that could be preserved.

10.2. Biophysical limit

We determined that there should be no limitation for preserve forests on agricultural land, thus the limit was set at 100%. This number would need to be improved based on a more accurate assessment of where forest conversion is possible and what land use the conversion is likely to result in. There was no reported uncertainty associated with the biophysical limit.

10.3. GHG reduction factor

The FL-CL conversion rate used by ECCC is the average annual forest conversion determined by interpolation of the remote sensing mapping of land-use area change between available Landsat images dated circa 1975, 1990, 2000, 2007, and 2011 (Environment and Climate Change Canada, 2020). For example, a 100 ha forest conversion during the four years from 2007 to 2011 would yield a 25 ha year^{-1} rate (100 ha/4 years) and this rate would be assigned to each year within the period 2007-2011.

According to A3.5.2 and A3.5.4 of NIR report (Environment and Climate Change Canada, 2020), the GHG emission associated with forest conversion is simulated using the CBM-CFS3 model as a result of net changes among different C pools (Environment and Climate Change Canada, 2020).

We assumed that future conversion of forest to cropland will be similar to that of the recent past. Thus, we used ECCC LULUCF data from the most recent five years (2014-2018) to calculate mean RF, RF uncertainty, and the bio-physical limit of activity units (Table A 25).

$$RF = \frac{FLCL\ emission}{FLCL\ conversion\ area} \times tonne\ conversion \times emission\ reduction\ modifier$$

$$= \frac{194\ kt\ CO_2e\ year^{-1}}{1980\ ha^{-1}} \times 1000\frac{t}{kt} \times (-1) = -97.98\ t\ CO_2e\ \ ha^{-1}year^{-1}$$

The RF was calculated under the assumption that “immediate emissions” (from the year of conversion) would be avoided. CO_2 emissions from litter and woody debris are included in both "immediate emission" and “residual emissions” NIR sub-categories; CO_2 emissions from soil are not included in emission estimates from forestland conversion to cropland in Western Canada. Thus, our RF estimates capture avoidance of CO_2, N_2O, and CH_4 emissions from logging, uprooting and burning (from biomass, litter, and woody debris), but do not capture all CO_2 emissions from forest floor /soil processes. For Western Canada, CanSIS data indicated no loss of SOC over the long-term from forest conversion to pasture and forage crops, where most forest conversion takes place (Environment and Climate Change Canada, 2020). The source of GHG emission from forest conversion in Western Canada would mainly be CO_2 from losses of C in above- and belowground tree biomass and coarse woody organic matter rather than soil C (Environment and Climate Change Canada, 2020) Therefore, our estimates are likely to be more accurate for FL-CL converted to pasture and forage croplands, but under-estimating GHG emission reductions for FL-CL converted to more intensive cropping systems where larger changes in soil organic matter are expected.

We extracted the emission factor (EF) uncertainty of "LULUCF - Conversion of Forest Land" given by the NIR (Environment and Climate Change Canada, 2020) as the uncertainty for annual GHG emission of FL-CL conversion (15%). The uncertainty associated with the FL-CL area (30%) is extracted from *A3.5 Methodology for the Land Use, Land-Use Change and Forestry Sector* of the National Inventory Report (Environment and Climate Change Canada, 2020). The combined RF uncertainty is then calculated by combining uncertainties using Equation 0-3a as:

$$Uncertainty = \sqrt{(uncertainty\ of\ EF)^2 + (uncertainty\ of\ activity\ data)^2}$$
$$= \sqrt{0.15^2 + 0.30^2} = 34\%$$

Table A 25. *Forestland-cropland conversion rate (ha year^{-1}) and the immediate GHGs emission (2014-18).*

Year	FLCL emissions	EF uncertainty	FLCL area	Activity data uncertainty	RF	RF uncertainty
	kt CO_2e yr^{-1}	%	ha	%	t CO_2e ha^{-1} yr^{-1}	%
2014	185	15%	1980	30%	-93.43	34%
2015	182	15%	1980	30%	-91.92	34%
2016	220	15%	1980	30%	-111.11	34%
2017	188	15%	1980	30%	-94.95	34%
2018	195	15%	1980	30%	-98.48	34%
5-year mean	**194**	**15%**	**1980**	**30%**	**-97.98**	**34%**

10.4. Maximum GHG benefit potential

We calculated the maximum GHG benefit potential as:

$Max. GHG\ benefit\ potential = reduction\ factor \times total\ activity\ units \times biophysical\ limit = -97.98\ t\ CO_2e\ \ ha^{-1}year^{-1} \times 1980\ \ ha^{-1} \times \frac{1\ kt}{1000\ t} \times 100\% = -194\ kt\ CO_2e\ year^{-1}$We also assigned a 100% uncertainty to this estimated maximum area of forest preserved annually. The biophysical limit of this BMP is assumed to be 100%.

Combined uncertainty is calculated using Equation 0-3a**:**

$$Combined\ uncertainty\ of\ Max.potential\ GHG\ reduction$$
$$= \sqrt{(uncertainty\ of\ RF)^2 + (uncertainty\ of\ activity\ data)^2}$$
$$= \sqrt{0.41^2 + 1^2} = 101\%$$

10.5. Cost of adoption

We estimated the cost of preserving forest from conversion to cropland based on the estimates of what farmers would require in a reverse auction program to preserve trees on their land for 20 years (CA$ 2363.71 ha^{-1}) as reported by the FCS economics report (De Laporte, Schuurman, & Weersink, 2021). The annual cost of preserving forest from conversion to cropland by 2030 is CA$ 118.19 ha^{-1} $year^{-1}$.

10.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 26. *Summary of qualitative scoring for BMP: Preserve forest from conversion to cropland.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	4	Long term GHG benefits; no decrease in benefits over time	3	Uncertainty is low, based on expert, anecdotal evidence
MRV feasibility	3	The methods are well-established and accepted widely	N/A	N/A
Soil quality	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	4	Uncertainty is low, based on concrete evidence

Water quality / conservation	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	4	Uncertainty is low, based on concrete evidence
Air quality	4	This co-benefit will be significantly increased by this practice, and/or benefits substantially outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Biodiversity / pest management	3	This co-benefit will be increased by this practice and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Adaptation	3	This co-benefit will be increased by this practice and/or benefits outweigh harms	4	Uncertainty is low, based on concrete evidence

10.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *Is the 1980 ha/year on private or crown land that is being developed under the extensive agriculture mechanism?*
- *An assessment of land agricultural capability may inform this, as there could be a difference in level of adoption depending on potential return. Additionally, the type and size of farm operation may be factors as some production types may be more compatible with the BMP and different scale operations may have different pressures on land use.*
- *Has the opportunity cost in regard to food security and other matters been determined? It is unclear if the reverse action figures reflect willingness of BC landowners or those from another jurisdiction, differing land values across jurisdictions may be factor, BC specific numbers would be beneficial. Were any possibilities related to having harvestable foods from maintained private land forests eg. where some economic benefit could be derived by land owner in addition to the "rent"?*
- *Regarding qualitative scoring, financial risk may vary on a 20 year horizon, may be premature to indicate no impact.*

A.11. BMP: Replace tractors with electric tractors

GHG emissions from operating diesel- or gas-powered farm machinery contribute to the Energy – off-road fuel combustion category of GHG inventory, mainly in the form of CO_2. Here we provide details for calculating the GHG benefit potential of replacing fossil fuel-powered tractors with electric in BC.

11.1. Total activity units

The Agriculture Census published by Statistics Canada in 2016 reported 41,986 tractors being operated on farms in BC (Statistics Canada, 2021). ECCC reported 168 kt CO_2e $year^{-1}$ emissions from on-farm transportation in BC in 2016 (Environment and Climate Change Canada, 2021).

11.2. Biophysical limit

We assume that 100% of the fossil fuel-powered tractors could be replaced with electric ones.

11.3. GHG reduction factor

We assumed that 100% of fuel consumption for on-farm transportation is for tractor operation. The average GHG emission reduction factor (RF) per tractor was then calculated as:

$$RF = \frac{Annual\ emission\ of\ on\ farm\ transportation}{Total\ number\ of\ tractor\ on\ farm\ in\ BC} \times \frac{1000\ t}{1\ kt} \times reduction\ modifier$$

$$= \frac{168\ kt\ CO2e}{41{,}986\ tractor} \times \frac{1000\ t}{1\ kt} \times (-1) = -4.09\ t\ CO_2e\ tractor^{-1} year^{-1}$$

11.4. Maximum GHG benefit potential

The maximum GHG benefit potential was then calculated as:

$$GHG\ benefit = RF \times Total\ number\ of\ tractors \times \frac{1\ kt}{1000\ t} = -4.95 \times 41{,}986 \times \frac{1}{1000}$$

$$= -168.04\ kt\ CO_2e\ year^{-1}$$

We extracted the combined uncertainty (1.1%) of *Fuel Combustion – Off-road* (IPCC Emission Source Category 1.A.2-3-4) (Environment and Climate Change Canada, 2020) to use as the uncertainty of GHG emission of on-farm transportation.

11.5. Co-benefit: Cost of adoption

According to an article posted on The Western Producer, the average price of an electric tractor is roughly CA$50,000 (Lyseng, 2019).

11.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 27. *Summary of qualitative scoring for BMP: Replacing tractors with electric tractors.*

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	4	Long-term GHG benefits, no decrease in benefits over time	3	Uncertainty is low, based on expert, anecdotal evidence
MRV feasibility	1	There has been some methods development	N/A	N/A
Soil quality	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Water quality / conservation	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Air quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Biodiversity / pest management	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	3	Uncertainty is low, based on expert, anecdotal evidence
Financial risks / benefits	1	This co-benefit will be decreased by this practice, and/or harms outweigh benefits	1	Uncertainty is high
Adaptation	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	2	Uncertainty is low, based on non-expert judgement

Regulation barriers	4	Requires no approval, or requires a simple permit	3	Uncertainty is low, based on expert, anecdotal evidence

11.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *What is the current extent of electric tractor adoption?*
- *For this BMP to be viable, electric tractors need to be available in the market, be able to perform comparable to traditional tractors and be serviceable. In more remote areas like the Northern parts of BC were large tracts of agricultural land occur, serviceability of this relatively new technology may greatly hinder adoption. An assessment of land agricultural*
- *How many farm operations/forage fields in BC are still off the electricity grid? Could this still be a barrier?*
- *Unless a producer needs to replace a tractor, I would not foresee a large uptake. These are large investments that would require a significant cost share to make this BMP appealing enough to replace an otherwise well-functioning tractor.*
- *Does the calculation include the GHG emission of electric tractors? Electrical batteries require elements that require mining (such as silver) which can be a large source of GHG emission. These source emissions should also be considered in the overall effectiveness of a technology to reduce GHG emission.*

A.12. BMP: Rotational grazing

Grazing land in BC has potential to mitigate GHG emissions by acting as a C sink when managed properly. In contrast to continuous grazing where livestock continuously graze in a single paddock, rotational grazing is the practice of circulating grazing livestock through multiple, separate paddocks. Studies have shown that rotational grazing can increase vegetation growth, provide better forage quality, and increase soil organic carbon (SOC) (Sanderman et al. 2015, Wang et al. 2015, Byrnes et al. 2018, Alemu et al. 2019). This synopsis will calculate the GHG reduction factor (RF) of rotational grazing and the GHG benefit potential of implementing rotational grazing in BC.

12.1. Total activity units

We extracted the total area of pasture land (tame and natural) from Statistics Canada (Statistics Canada, 2021) (Table 9-4).

12.2. Biophysical limit

The Farmers for Climate Solutions (FCS) report (Burton, McConkey, & MacLeod, 2021) estimated multiple adoption scenarios and we assumed that the *ambitious* scenario is an accurate estimate of the biophysical limit of implementing rotational grazing in BC (Table A 28).

Table A 28. *Total area of pasture land in BC and the biophysical limit of implementing rotational grazing.*

Type of pasture	Rotational grazing method	Area of pasture land	Biophysical limit
		ha	% of area
Tame pasture	Basic	205,872	15%
Tame pasture	Intensive	205,872	20%
Natural pasture	Basic	1,433,202	20%
Natural pasture	Intensive	1,433,202	15%

12.3. GHG reduction factor

The FCS report (Burton, McConkey, & MacLeod, 2021) performed an extensive analysis on the GHG mitigation effects of rotational grazing relative to continuous grazing through two pathways: (1) change in soil carbon sequestration (Cseq) rate relative to continuous grazing, and

(2) reduced enteric fermentation relative to continuous grazing. These effects were estimated for 5 classes of grazing:

- Continuous;
- Basic – Simple;
- Basic – Advanced;
- Intensive – Simple;
- Intensive – Advanced.

For simplicity, we chose the *Advanced Basic* and *Simple Intensive* classes as the specific BMPs to be evaluated and we renamed them to '*Rotational grazing – basic'* and '*Rotational grazing – intensive'* in this BMP synopsis, and in the MCF excel and report. The FCS report also estimates GHG mitigation effects for two pasture types (natural land and tame land) and three climatic zones in Canada (moist and warm, dry, and moist and cool). The FCS report defined "moist and warm" as mixed wood plains, Atlantic maritime, and Pacific maritime, "dry" is the Brown and Dark Brown soil zones of Alberta and Saskatchewan, "moist and cool" Canada is the remainder of Canada that is either situated north of warm and moist or subhumid western Canada (Burton, McConkey, & MacLeod, 2021). We included both pasture types in our analysis. Given that the majority of grazing land in BC is located in the Montane Cordillera Ecozone, we extracted the GHG mitigation effect data of *Moist and cool Canada* from the FCS report (Burton, McConkey, & MacLeod, 2021) (Table A 29). We calculated the BMP benefit potential for four different rotational grazing scenarios: (1) Basic rotational grazing– tame pasture, (2) Intensive rotational grazing – tame pasture, (3) Basic rotational grazing – natural pasture, and (4) Intensive rotational grazing – natural pasture.

Table A 29. *GHG mitigation effects of rotational grazing relative to continuous grazing.*

Type of pasture	**Rotational grazing method**	**Change of Cseq rate**	**Emission reduction for enteric fermentation**
		kg C ha^{-1} $year^{-1}$	kg CO2e ha^{-1} $year^{-1}$
Tame pasture	Basic	120	330
Tame pasture	Intensive	240	780
Natural pasture	Basic	60	165
Natural pasture	Intensive	120	600

The GHG reduction factor for the change in soil Cseq rate (Δ Cseq), relative to continuous grazing, with implementing rotational grazing is calculated as:

$$RF\ of\ \Delta\ Cseq\ (t\ CO_2e\ ha^{-1}year^{-1}) = \Delta\ Cseq\ (kg\ C\ ha^{-1}year^{-1}) \times CO_2e\ conversion\ \left(\frac{44}{12}\right) \times \frac{1\ t}{1000\ kg} \times reduction\ conversion(-1)$$

Taking ‘basic rotational grazing - tame pasture’ as an example:

$$RF\ of\ \Delta\ Cseq\ (t\ CO_2e\ ha^{-1}year^{-1}) = \Delta\ Cseq\ (kg\ C\ ha^{-1}year^{-1}) \times CO_2e\ conversion\ \left(\frac{44\ kg\ \mathrm{CO_2e}}{12\ kg\ C}\right) \times \frac{1\ t}{1000\ kg} \times (-1)$$

$$= 120\ (kg\ C\ ha^{-1}year^{-1}) \times CO_2e\ conversion\ \left(\frac{44\ \mathrm{kg\ CO_2e}}{12\ kg\ C}\right) \times \frac{1\ t}{1000\ kg} \times (-1) = -0.44\ t\ CO_2e\ ha^{-1}year^{-1}$$

The GHG reduction factor of reduced enteric fermentation emission (Δ CH_4), relative to continuous grazing, is calculated as:

$$RF\ of\ \Delta CH_4\ (t\ CO_2e\ ha^{-1}year^{-1}) = \Delta CH_4\ \ (kg\ CO_2e\ ha^{-1}year^{-1}) \times \frac{1\ t}{1000\ kg} \times reduction\ conversion(-1)$$

Taking ‘basic rotational grazing - tame pasture’ as an example:

$$F\ of\ \Delta CH_4\ (t\ CO_2e\ ha^{-1}year^{-1}) = \Delta CH_4\ \ (kg\ CO_2e\ ha^{-1}year^{-1}) \times \frac{1\ t}{1000\ kg} \times reduction\ conversion(-1)$$

$$= 330\ (kg\ CO_2e\ ha^{-1}year^{-1}) \times \frac{1\ t}{1000\ kg} \times (-1)$$

$$= -0.33\ t\ CO_2e\ ha^{-1}year^{-1}$$

The combined RF of these two GHG mitigation effects is calculated as:

$$RF_{Combined}\ (t\ CO_2e\ ha^{-1}year^{-1}) = RF_{\Delta Cseq} + RF_{\Delta CH_4}$$

The combined RF of 'basic rotational grazing - tame pasture' is calculated as:

$$RF_{Combined}\ (t\ CO_2e\ ha^{-1}year^{-1}) = RF_{\Delta Cseq} + RF_{\Delta CH_4}\ = (-0.44) + (-0.33)$$
$$= -0.77\ t\ CO_2e\ ha^{-1}year^{-1}$$

Reduction factors, RF_{Cseq}, RF_{CH4}, and $RF_{Combined}$, for the four rotational grazing systems have been calculated and are summarized in Table A 30.

Table A 30. *Reduction factors of each GHG mitigation effect and the combined reduction factor of rotational grazing.*

Type of pasture	**Rotational grazing method**	**RF_{Cseq}**	**RF_{CH4}**	**$RF_{Combined}$**
		t CO2e ha^{-1} year^{-1}	t CO2e ha^{-1} year^{-1}	t CO2e ha^{-1} year^{-1}
Tame pasture	Basic	-0.44	-0.33	-0.77
Tame pasture	Intensive	-0.88	-0.78	-1.66
Natural pasture	Basic	-0.22	-0.17	-0.39
Natural pasture	Intensive	-0.44	-0.60	-1.04

The FCS report (Burton, McConkey, & MacLeod, 2021) estimated that the relative change of soil Cseq rate has an uncertainty of 100%, but did not provide a quantitative estimation for the uncertainty of reduced enteric fermentation. We extracted the uncertainty associated with the 'enteric fermentation' emissions subcategory reported by the NIR (22 %) (Environment and Climate Change Canada, 2020) to use as the uncertainty for enteric fermentation reductions. Therefore, combined RF uncertainty is calculated using the additive error propagation Equation 1-3b:

$$Uncertainty\ of\ Combined\ RF = \frac{\sqrt{\left(RF_{\Delta Cseq} \times Uncertainty_{\Delta Cseq}\right)^2 + \left(RF_{\Delta CH_4} \times Uncertainty_{\Delta CH_4}\right)^2}}{|RF_{\Delta Cseq} + RF_{\Delta CH_4}|}$$

Taking ‘basic rotational grazing - tame pasture’ as an example:

$$Uncertainty\ of\ Combined\ RF = \frac{\sqrt{(-0.44 \times 100\%)^2 + (-0.33 \times 22\%)^2}}{|-0.44 - 0.33|} = 58\%$$

Uncertainty of RFs were calculated and summarized in Table A 31.

Table A 31. *Uncertainties associated with different GHG reduction factors.*

Type of pasture	Rotational grazing method	RF_{Cseq}	Uncertainty of RF_{Cseq}	RF_{CH4}	Uncertainty of RF_{CH4}	$RF_{Combined}$	Uncertainty of $RF_{Combined}$
		t CO2e ha^{-1} $year^{-1}$	%	t CO2e ha^{-1} $year^{-1}$	%	t CO2e ha^{-1} $year^{-1}$	%
Tame	Basic	-0.44	100%	-0.33	22%	-0.77	58%
Tame	Intensive	-0.88	100%	-0.78	22%	-1.66	54%
Natural	Basic	-0.22	100%	-0.17	22%	-0.39	58%
Natural	Intensive	-0.44	100%	-0.60	22%	-1.04	44%

12.4. Maximum GHG benefit potential

The maximum GHG benefit potential can be calculated as:

$$Maximum\ GHG\ benefit\ (kt\ CO_2e\ year^{-1}) = RF(t\ CO_2e\ ha^{-1}year^{-1}) \times Activity\ units\ (ha) \times Biophysical\ limit\ (\%) \times \frac{1\ kt}{1000\ t}$$

Taking ‘basic rotational grazing - tame pasture’ as an example:

$$Max. GHG\ benefit\ of\ \Delta Cseq\ (kt\ CO_2e\ year^{-1})$$

$$= RF_{\Delta Cseq}\ (t\ CO_2e\ ha^{-1}year^{-1}) \times tame\ pasture\ area\ (ha) \times Biophysical\ limit\ (\%) \times \frac{1\ kt}{1000\ t}$$

$$= -0.44\ (t\ CO_2e\ ha^{-1}year^{-1}) \times 205{,}872\ (ha) \times 15\% \times \frac{1\ kt}{1000\ t}$$

$$= -13.59\ kt\ CO_2e\ year^{-1}$$

$$Max. GHG\ benefit\ of\ \Delta CH_4\ (kt\ CO_2e\ year^{-1})$$

$$= RF_{\Delta CH_4}\ (t\ CO_2e\ ha^{-1}year^{-1}) \times tame\ pasture\ area\ (ha) \times Biophysical\ limit\ (\%) \times \frac{1\ kt}{1000\ t}$$

$$= -0.33\ (t\ CO_2e\ ha^{-1}year^{-1}) \times 205{,}872\ (ha) \times 15\% \times \frac{1\ kt}{1000\ t}$$

$$= -10.19\ kt\ CO_2e\ year^{-1}$$

$$Max. GHG\ benefit\ combined\ (kt\ CO_2e\ year^{-1})$$

$$= RF_{Combined}\ (t\ CO_2e\ ha^{-1}year^{-1}) \times tame\ pasture\ area\ (ha) \times Biophysical\ limit\ (\%) \times \frac{1\ kt}{1000\ t}$$

$$= -0.77\ (t\ CO_2e\ ha^{-1}year^{-1}) \times 205{,}872\ (ha) \times 15\% \times \frac{1\ kt}{1000\ t}$$

$$= -23.78\ kt\ CO_2e\ year^{-1}$$

Table A 32 summarized the calculated maximum GHG benefit of each GHG mitigation effect and the combined GHG benefit.

Table A 32. *GHG benefit of two rotational grazing method on two type of pasture.*

Type of pasture	Rotational grazing method	Max. GHG benefit of ΔCseq	Max. GHG benefit of ΔCH_4	Combined GHG benefit
		kt CO2e year^{-1}	kt CO2e year^{-1}	kt CO2e year^{-1}
Tame	Basic	-13.59	-10.19	-23.78
Tame	Intensive	-36.23	-32.12	-68.35
Natural	Basic	-63.06	-48.73	-111.79

Natural	Intensive	-94.59	-128.99	-223.58
All pasture	Basic	-76.65	-58.92	-135.57
All pasture	Intensive	-130.82	-161.1	-291.93

12.5. Cost of adoption

According to the FCS economic report (De Laporte, Schuurman, & Weersink, 2021), the cost of 10% new adoption is CA$ 24.22 ha^{-1}. We assume this cost stay the same when adoption rate is equal to or below the biophysical limit.

12.6. Qualitative scores

For each BMP we determined qualitative scores for other GHG, environmental, and financial outcomes to assess the potential co-benefit synergies and/or trade-offs with quantitative criteria (i.e., short-term GHG benefits and adoption costs). Methods for scoring are described in the MCF report **Section 3.4.2. Quantitative scoring in the MCF**, and the qualitative scales are provided in **Appendix B – Qualitative scales.**

Table A 33. Summary of qualitative scoring for BMP: Rotational grazing.

Criteria	Performance Score		Uncertainty	
Long-term GHG benefits	3	Long-term GHG benefits, but with decreased benefits over time	2	Uncertainty is low, based on non-expert judgement
MRV feasibility	2	The methods are developed but are costly, with high uncertainty and are not widely accepted	N/A	N/A
Soil quality	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Water quality / conservation	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Air quality	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	2	Uncertainty is low, based on non-expert judgement
Biodiversity / pest management	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence

Financial risks / benefits	2	This co-benefit will not be impacted by this practice, or harms and benefits offset	1	Uncertainty is high
Adaptation	3	This co-benefit will be increased by this practice, and/or benefits outweigh harms	3	Uncertainty is low, based on expert, anecdotal evidence
Regulation barriers	3	Requires a permit, but <6-month process, or other paperwork (i.e., taxes) creating a similar burden / obstacle	2	Uncertainty is low, based on non-expert judgement

12.7. Feedback collected for refinement of this BMP

Next steps in the development of data for this BMP should include consideration of the following feedback collected from AFF agrologists:

- *Next steps should include discussions with FLNR range staff to review this BMP to assess the baseline grazing regime that best reflects current practice in BC.*
- *Based on statement in Section 14.1 indicating that pasture land area taken from Statistics Canada, I assume this relates to private land pasture. Many cow-calf operations in BC rely on seasonal grazing of Crown Land range as part of their production cycle, this area (while often having different characteristics than private pasture) far exceeds the amount of area in private land pasture. May be beneficial to clarify land base under discussion, and also consider if/how Crown range should be treated in analysis. If crown range were considered, FLNRORD may be able to provide information on current use of some form or rotation in multi-year plans.*
- *It is unclear if the adoption potential is from no rotation to some level of rotation (basic or intensive) or from basic to to intensive or the maintaining of either basic or intensive rotational management.*
- *Given the definitions of Basic, advanced and intensive, simple in the FCS report and given that the report refences Manitoba data caution may be required in interpretation given different growing conditions, growing season precipitation patterns and other factors related to regrowth particularly for native pastures where irrigation is less common and larger paddocks may be used. Pastures where irrigation is in place may be more easily adapted to higher intensity rotations.*

- *In regard to Section 14.2 it s unclear how the current management of pasture land is being estimated/considered, some form of rotational grazing is used by many operators in BC and for those cow-calf operations using crown range, range use plans typically include the specifics of the rotation. Granted in many situations the scale of the rotation may not be as intensive as others. Looking at the FCS report it appears to reflect national percentages relating to rotational grazing - is it known if these percentages are reflected in BC?*
- *It is unclear how the factor addresses incremental change vs continuation of existing rotational management (where already in place).*
- *It is unclear if 'moist and cool' Canada fits for all areas used for grazing in the Montane Cordillera, for example Stats Can data shows ~1/3 of beef cows are located in the Thompson Okanagan which one would assume is in the dryer/warmer range with cattle often found in BEC zones such as BG, PP, and IDF and a further 22% in the Cariboo.*
- *Cost of adoption appears to reference the FCS report which in turn references capital costs from Manitoba; it is unclear of the type of fencing implemented which will have direct bearing on costs e.g. electric vs permanent 4 strand wire. BC pasturelands includes many areas with diverse topography and in turn fencing and water development can be challenging in some areas. Current estimates used for fencing costs for 4 strand barbed wire fencing with posts can typically vary between $15-20K per km depending on conditions. Depending on location of fence additional steps including consultations and assessments may be needed, these factors can have cost impacts. Suggest additional detail be provided in regard to adoption data including ongoing costs particularly if information will be used to engage producers.*
- *Regarding qualitative data, this BMP has many co-benefits including production related benefits. Regarding regulatory barriers, this will depend on fence locations, and consultations and assessments may contribute to longer timeframes.*
- *One of the allowable costs should be the use of portable electric fences. This is often not permissible in BMP programs for fear that the fencing will be used for other purposes. However, portable fences are key to the implementation and success of the more advanced rotational grazing practices, which is what we would like for producers to adopt in the end. Additionally, I have heard feedback from producers who built more*

permanent fences early on and now are realizing that these permanent fences are actually hindering them in fully implementing more advanced rotational grazing regimes, or in other cases, the permanent fence turns out to be in a location that no longer serves a growing operation and now needs to be removed regardless. These are just some of the reasons why I would advocate to allow for temporary electric fence support as part of a BMP that is intended to promote rotational grazing.

- *Significant benefits could arise by taking simple rotational grazing (which is still rather extensive and uses low stock density) to a more advanced rotational grazing system (which uses a more intensive management system with higher stock densities).*
- *The lack of a provincial forage specialist may have added to the gap of education and awareness being made available to producers.*
- *General, one size fits all rotational grazing templates will not be meaningful to for successful BMP implementation. Working with individual producers and adjusting their systems based on their current situation would be the level of support required to achieve the positive impact intended through this BMP.*
- *This BMP could also be paired with the cover crop BMP by encouraging grazing of cover crops to 50% of vegetative cover using high intensity, short duration grazing practices to also achieve significant trampling of the cover crop into the soil to facilitate decomposition and integration of the cover crop.*
- *The level of adoption will largely depend on the definition of rotational grazing desired. As outlined in your report, simple rotational grazing will not be as beneficial as more advanced rotational grazing practices.*

Appendix B – Qualitative scales

Table B 1. *Qualitative Scale A - GHG benefits >2030.*

Value	Score	Score Description	Scaled Value
0	Very negative impacts	• Very likely to cause net GHG emissions in long term	0
1	Somewhat negative impacts	• Possibility for some net GHG emissions in long term	25
2	Neutral	• No long term GHG benefits; only short-term (~10 years) after BMP implementation	50
3	Somewhat positive impacts	• Long term GHG benefits, but with decreased benefits over time	75
4	Very positive impacts	• Long term GHG benefits, no decrease in benefits over time	100

Table B 2. *Qualitative Scale B - GHG benefits - MRV feasibility.*

Value	Score	Score Description	Scaled Value
1	No methods	• No work has been done to develop methods	0
2	Methods are not close to operational	• There has been some methods development	25
3	Methods are somewhat operational	• The methods are developed but are costly, with high uncertainty and are not widely accepted	50
4	Methods are operational	• The methods are well established and accepted widely	75
5	Methods are very operational	• Methods are cost effective, with low uncertainty specifically for BC	100

Table B 3. *Qualitative Scale C – Environmental co-benefits, financial risks/benefits, and adaptation benefits.*

Value	Score	Score Description	Scaled Value
0	Very negative impacts	• this co-benefit will be significantly decreased by this practice, and/or • harms substantially outweigh benefits	0

1	Somewhat negative impacts	• this co-benefit will be decreased by this practice, and/or • harms outweigh benefits	25
2	Neutral	• this co-benefit will not be impacted by this practice, or • harms and benefits offset	50
3	Somewhat positive impacts	• this co-benefit will be increased by this practice, and/or • benefits outweigh harms	75
4	Very positive impacts	• this co-benefit will by significantly increased by this practice, and/or • benefits substantially outweigh harms	100

Table B 4. *Qualitative Scale D - Regulatory barriers.*

Value	Score	Score Description	Scaled Value
0	Not possible	• Practice is currently prohibited • Requires legislation change	0
1	Large barriers; complicated process	• Requires a permit; 2+ year approval process; approval not guaranteed • Or, other paperwork (i.e. taxes) creating a similar burden / obstacle	25
2	Moderate or unknown barriers	• Requires a permit; 6 month – 2 year approval process • Or, other paperwork (i.e. taxes) creating a similar burden / obstacle	50
3	Small barriers; straightforward process	• Requires a permit, but <6-month process • Or, other paperwork (i.e. taxes) creating a similar burden / obstacle	75
4	Little to no barriers	• Requires no approval, or • Requires a simple permit	100

Table B 5. *Qualitative scale E – Qualitative uncertainty.*

Value	Score	Description	Scaled Value
0	Very high uncertainty	• Uncertainty is very high, regardless of expert vs. non-expert judgement	0
1	High uncertainty	• Uncertainty is high	25
2	Moderate uncertainty	• Uncertainty is low, • based on non-expert judgement	50

3	Low uncertainty	• Uncertainty is low, • based on expert, anecdotal evidence	75
4	Very certain	• Uncertainty is low, • based on concrete evidence	100