GHG Analysis and Quantification

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1. Improved Nitrogen Management for Nitrous Oxide Emissions Reduction

Introduction

The use of nitrogen (N) fertilizer in agriculture results significant greenhouse gas emissions in across Canada (Fig. 1.1). Here we consider the opportunities for improved nitrogen (N) management to reduce N_2O emissions associated with N fertilizer. In addition, fertilizer N management has the capacity to reduce the carbon footprint of agriculture through its potential to increase soil organic carbon stocks. Improved N management also offers other environmental benefits such as a reduction in the leaching of nitrate (NO_3^-) to groundwater and ammonia (NH_3) emissions to air. These other environmental services may prove to be at least as important as the reduction of GHG emissions in terms of both impact on the environment and in motivating governments and producers to adopt improved N management practices.

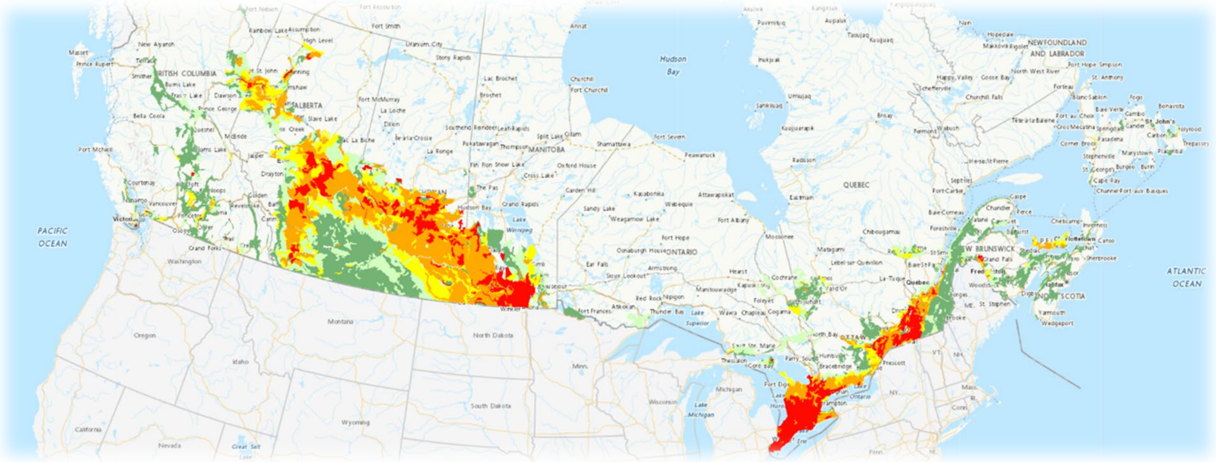

Figure 1.1: Greenhouse gas emissions from fertilizer[1]. Legend Red – Very High (> 3.0 kg N_2O-N ha^{-1}); Orange – High (2.1 to 3.0 kg N_2O-N ha^{-1}); Yellow – Moderate (1.6 to 2.0 kg N_2O-N ha^{-1}); Pale Green – Low (1.1 to 1.5 kg N_2O-N ha^{-1}); Dark Green – Very Low (< 1.0 kg N_2O-N ha^{-1}).

Methods for Estimating Nitrous Oxide Emissions

In our national inventory, N_2O emissions are not measured directly but rather are estimated based on N inputs. The basic calculation procedures are a Tier 2 method (Rochette *et al.*, 2008) as implemented in Canada's National Inventory Report (Environment and Climate Change Canada, 2020). The method accounts for effect of regional differences in the climate to alter direct emission factors with further modifications based on soil texture, tillage, topography, and fallow. The inventory does not currently capture emissions reductions resulting from differences in N

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[1] Source: https://open.canada.ca/data/en/fgpv_vpgf/5fec775d-7c91-4ab5-bb63-6db4627e52a0

management. Indirect N_2O emissions are also estimated based on emission factors adjusted for regional climate. For this analysis, estimation of direct and indirect N_2O emissions were based on crop specific N fertilizer use and area cropped reported for 3,482 soil landscape polygons, data collected as part of the 2017 Farm Environmental Management Survey conducted by Agriculture and Agri-Food Canada.

These estimates of N_2O emissions assume a linear relationship between N fertilizer application rate and N_2O emissions. At higher rates of N fertilization this approach may underestimate N_2O emissions as it is well documented that the N_2O emission factor increases as the rate of N fertilizer application exceeds plant N demand (Eagle et al., 2017; Van Groenigen et al., 2010).

One of the challenges of managing agricultural N_2O emissions is that it is difficult for producers to directly measure N_2O emissions and therefore assess the extent of these emissions in their production systems. Secondly, greenhouse gas emissions reduction does not represent a direct cost to the producer and therefore is not necessarily a priority for all producers. Providing producers with a practical means of assessing N use efficiency would allow them to understand progress toward both reduced environmental impact and increased agronomic efficiency. It could also help to inform Agri-Environmental Indicators and the National Inventory so that they reflect differences in emissions as a result of differences in nitrogen management.

One practical measure of N use efficiency is to measure the amount of nitrate[2] remaining in the soil following the harvest of the crop. This concept also forms the basis of one of Agriculture and Agri-Food Canada's Agri-environmental Indicators residual soil nitrogen (RSN) (Clearwater et al., 2016). RSN is calculated as the difference between N inputs (N fertilizer, manure, crop residue) and N outputs (harvest N). Note that in Canadian agricultural soils the majority of mineral N remaining in the soil in the fall would be in the form of nitrate (NO_3^-) as in these soils as nitrification would go to completion, converting ammonium (NH_4^+) to NO_3^-. RSN is an indicator of the potential for environmental impact on water, primarily as NO_3^- leaching, and air as a result of N_2O emissions. An examination of RSN over time in Canadian agriculture indicates a trend from negative values for RSN prior to 1985, indicating net removal of N from Canadian agroecosystems, primarily originating from soil N mineralization, to a condition of positive values for RSN, indicating N additions in excess of N removals and therefore an increase in the potential for N loss (Fig. 1.2). This is imbalance not only directly drives increased N_2O emissions and nitrate leaching, but it is also an indicator of the potential for N loss from Canadian agriculture.

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[2] Measuring nitrate is most appropriate and often sufficient as it is the form from which most N losses emanate and it is the primary form of plant available nitrogen that would be present in the soil at the end of the growing season.

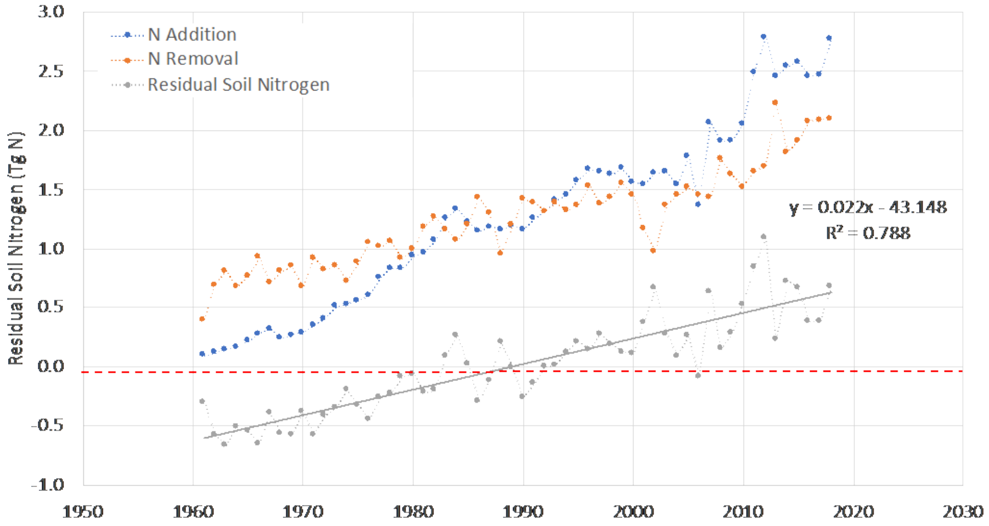

Figure 1.2: Residual soil nitrogen (Tg N), estimated as the difference between fertilizer N inputs and N removals, from 6 major crops in Canada (data from FAO)

4R Nutrient Management

In response to concerns relating to the potential for fertilizers to impact the environment, the fertilizer industry developed the 4R Nutrient Stewardship Program to promote improved fertilizer management. The 4R nutrient stewardship program refers to four key practices in nutrient management: 1) right source – choose plant-available nutrient forms that provide needed nutrients with release matched to crop demand, 2) right rate – ensure adequate, but not excessive, amounts of all limiting nutrients are applied to meet plant requirements in relation to yield and quality goals, 3) right time – time nutrient applications considering the interactions of crop uptake, soil supply, environmental risks, and field operation logistics, and 4) right place – place nutrients to take advantage of the root-soil dynamics, spatial variability within the field, and potential to minimize nutrient losses from the field (Reetz *et al.*, 2015).

In our modelling, we estimated the potential for N_2O emissions reduction from adoption of 4R fertilizer N management practices at three levels of implementation – basic, intermediate, and advanced (Table 1.1) for the five major cropping systems in Canada (Table 1.2). Direct N_2O emissions from chemical fertilizer N use were based on Business as Usual (BAU) trends in N fertilizer use projected for 2025 and 2030 in Prairie Canada and the rest of Canada (Fig. 1.3) and multiplied by a N_2O emissions reduction modifier for each level of implementation (Table 1.2). These N_2O emission reduction modifiers were drawn from a science review document, developed by a science panel hosted by Fertilizer Canada in Toronto in January 2018 in which 12 Canadian science experts in agricultural N_2O emissions participated. At the time it was judged that there was insufficient information to assign an increase in the reduction modifier for more advanced 4R implementation for potato production based on gaps in the existing literature. Here we have assumed that research has progressed and the implementation of more advanced 4R practices in potato production results in an increase in the reduction modifier.

Table 1.1: General definition of 4R implementation Level

	4R Implementation Level		
4R Practice	Basic	Intermediate	Advanced
Right Rate	N rate based on target crop removal and N status of soil, manure N estimated, based on individual field	Basic + sub-field zones based on land characteristics.	Intermediate + sub-field application based on in-depth field analysis, in-season crop monitoring, regular re-evaluation based on data.
Right Source	Ammonium-based fertilizer	Basic + enhanced efficiency fertilizers for at least 1/3 of the N used.	Intermediate + enhanced efficiency fertilizer for at least 1/2 the N used.
Right Time	Fertilizer applied in spring (fall when soil cool in prairies), split N for potato and corn, no application on snow or frozen soil	Basic + multiple fertigation (irrigated)	Same as Intermediate
Right Place	Placed in soil, no more than 1/3 on surface, sideband at seeding	No surface application unless incorporated with 1 day or with enhanced efficiency fertilizers	Same as Intermediate

Table 1.2: Definition of 4R practices constituting basic, intermediate and advanced implementation of 4R for major cropping systems in the Canadian Prairies and the Rest of Canada. Detailed descriptions are provided in Appendix A. EEF = enhanced efficiency fertilizer, RR = reduced rate of N fertilizer, SP = split fertilizer application†, VR = Variable Rate Application, RM = N_2O emission factor reduction modifier

	Basic	Intermediate	Advanced
Prairies			
Canola	Follow provincial rate recommendations RM = 0.85	EEF (1/3), RR, RM = 0.75	EEF (1/2), RR, VR RM = 0.65
Spring Wheat	Follow provincial rate recommendations RM = 0.85	EEF (1/3), RR, RM = 0.75	EEF (1/2), RR, VR RM = 0.65
Potato (irrigated)	Follow provincial rate recommendations RM = 0.85	EEF (1/3), RR, RM = 0.80	EEF (1/2), RR, VR RM = 0.75
Rest of Canada			
Corn	Follow provincial rate recommendations RM = 0.85	EEF (1/3), SP†(1/3), RR RM = 0.75	SP (1/3), EEF (1/2), RR, VR RM = 0.65
Winter wheat	Follow provincial rate recommendations RM = 0.85	EEF (1/3), RR RM = 0.75	SP (1/3), EEF (1/2), RR, VR RM = 0.65
Potato (rainfed)	Follow provincial rate recommendations RM = 0.95	EEF (1/3), RR, RM = 0.90	EEF (1/2), RR, VR RM = 0.80

[†] *Note in Canada Prairies the term "split nitrogen application" is often used to refer to a split between fall and spring application rather than splitting N applications during the growing season as the term is used in the rest of Canada.*

In this analysis, we considered the opportunity for 4R N management scenarios to reduce N_2O emissions in canola, spring wheat (including durum wheat), corn (grain and silage corn), winter wheat and potato production (irrigated in Prairie Canada, rainfed in the rest of Canada). These five crops represent 62% of the cropped ha in Canada and 61% of the N fertilizer use. These crops also represent the crops where there is the greatest available information on current N management and the potential for 4R N management to reduce N_2O emissions. It is expected that adoption of 4R management to other crops would also result in additional N_2O emissions reductions beyond those quantified here.

To quantify the mitigation potential of improved adoption of N management requires an understanding of the amount of N application expected in 2025 and 2030. The rate of increase in N fertilizer use is greater in Prairie Canada than in the rest of Canada (Fig. 1.3). The N fertilizer use from 1980 to 2019 was fit to both linear and exponential trendlines. The rate of N fertilizer use in the Prairies is increasing sharply, whereas the N fertilizer use in the rest of Canada has not increased significantly. For this analysis we used the more conservative linear prediction of the N fertilizer use in 2025 and 2030 (Table 1.3). This is in keeping with the goal of the program to slow the rate of increase in N fertilizer use through more efficient N fertilizer use. Should the growth in N fertilizer follow the exponential trendline, the N_2O emissions reductions would be approximately 35% higher than those modelled here. What is used to predict the "business as usual" trend (linear or exponential) is important in determining the magnitude of emissions reductions associated with the implementation of improved N fertilizer use are calculated. Greater emissions, and greater emissions reductions, can be achieved if it is assumed N fertilizer use will increase according to the exponential trend. Here, we assume that the emission reductions calculated are avoided annual emissions and therefore are reported as an absolute annual emissions reduction rather in reference to a baseline year.

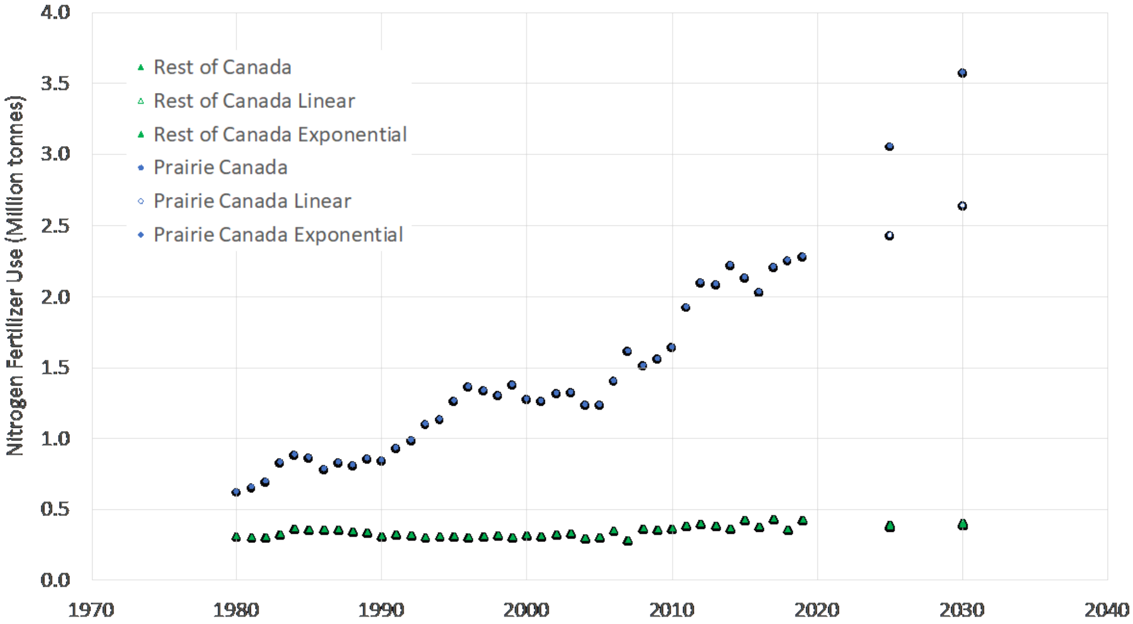

Figure 1.3: Historical trends in N fertilizer use in Prairie Canada and the rest of Canada in millions of tonnes. Prediction of N fertilizer use in each region according to a linear (open symbols) and exponential (closed symbols) curve fit.

Table 1.3: Predicted N fertilizer use (million tonnes y^{-1}) in Prairie Canada and the rest of Canada in 2025 and 2030 according to linear and exponential models.

	2025	2030
	Million Tonnes y^{-1}	
Prairie Canada (Linear)	2.43	2.64
Prairie Canada (Exponential)	3.06	3.58
Rest of Canada (Linear)	0.40	0.41
Rest of Canada (Exponential)	0.38	0.39

Adoption Rate Scenarios

Current rates of adoption of 4R practices are not currently reported and therefore we estimated 2017 baseline adoption values (Table 1.4) based on results of the 2019 survey of Canola growers and Ontario corn growers by Stratus Research (Stratus, 2019) commissioned by Fertilizer Canada. These estimates were drawn from responses regarding how nitrogen rate decisions were made and the use of variable rate and enhanced efficiency fertilizers.

Table1.4: Estimated baseline (2017) adoption rates for basic, intermediate, and advanced 4R management used in modelling.

	Basic	Intermediate	Advanced
Corn	27	22	11
Winter Wheat	30	20	10
Potato (rainfed)	30	20	10
Canola	45	12	6
Spring Wheat	30	20	10
Potato (irrigated)	30	20	10

Farmers are motivated by environmental concerns but are willing to incur only small additional costs for the sake of the environment (Amiro et al., 2017). Therefore, the degree of adoption depends on the cost of implementation versus the potential benefits and risk. There are two important economic risks: reduced yield as a result of lack of nutrients and applying excess fertilizer that does not result in significant yield gain (reducing economic return by narrowing the difference between profit and expenses). The basic 4R implementation level provides some reduction in both these risks. However, given the additional costs associated with intermediate and advanced implementation, the reduction in fertilizer application is not sufficient to compensate for additional costs of intermediate or advanced levels of 4R implementation. Therefore, the farmer may also have to identify and rectify areas where they had been applying insufficient nutrients to increase yields so as to recoup the increased costs of intermediate and advanced 4R implementation.

It is important to note that, currently, knowledge of 4R does not necessarily result in reduced fertilizer N or reduced N_2O emissions. In 2019, Ontario corn producers who indicated they were very familiar or somewhat familiar with 4R applied 28% higher rates of N fertilizer than those that were not familiar 4R practices (Stratus 2019). These higher rates of N fertilizer application were not offset by higher yields resulting in lower nitrogen response measured as the kg grain per kg N fertilizer added (Fig 1.4). Thus, familiarity of 4R practices did not translate into improved N management as expected, but rather resulted in poorer N use efficiency in 2019. This is also consistent with earlier surveys by Stratus (Stratus, 2015, 2016), which reported that producers who believed that they had good familiarity with 4R practices used a higher average rate of N fertilizer application than those who professed no familiarity with 4R practices. This underscores that knowledge of 4R practices is not sufficient to lead to improved N management. Selection of the right rate of N fertilizer application must consider actual yield potential with reflect the other factors that limit yield (i.e., weather, disease) must also be considered. In the Economic Analysis Report it is noted that small reductions in N rate may not change yields very much at all. Yanni et al. (2020) assumes that a 20 kg N/ha reduction from (170 to 150 kg N/ha) results in no yield loss on corn. De Laporte et al. (2020) shows that an average reduction in N rate from 176 kg N/ha to 124 kg N/ha results in an average corn yield loss of only about 1.1% across the province of Ontario over 30 years of weather with some other practice adaptations.

The benefits of the increased efficiency of 4R will only be expressed when they are coupled with a reduction in the rate of N fertilizer application to reflect the increase in efficiency (Zebarth et al., 2012). The complexity of developing farm-specific 4R management suites highlights the need for trained independent agronomic advice and measurement-based determinants of *Right Rate* to better understand the on-farm success of 4R management and to confirm the success of the 4R implementation. The measurement of residual soil nitrogen in the fall is an effective means of documenting increased efficiency of utilization of N fertilizer and reduced risk of N_2O emissions and NO_3^- leaching to groundwater.

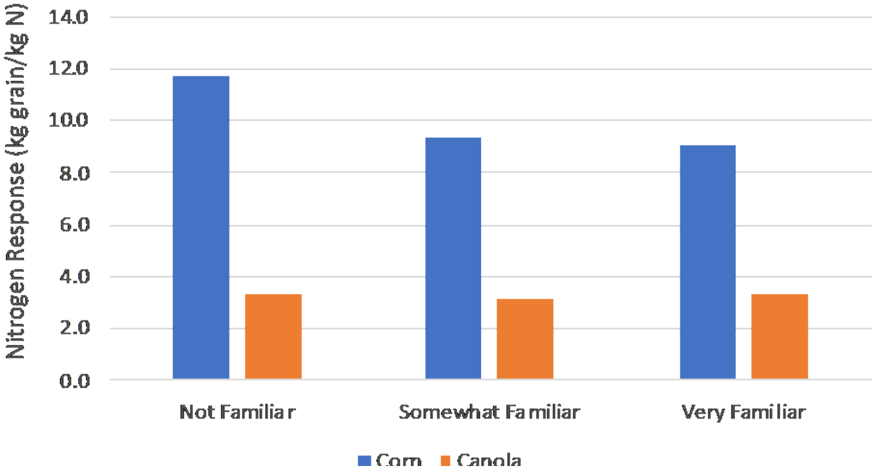

Figure 1.4: Nitrogen response (kg grain/kg N fertilizer) for corn production in Ontario and canola production in Prairie Canada in 2019 (data from Stratus, 2019).

Two different scenarios describing improved adoption of 4R levels were modelled. The first, we refer to as *strong foundation (SF)*. It emphasizes maximum adoption of basic and intermediate levels of implementation with limited reliance on enhanced efficiency fertilizers (a critical part of advanced implementation). The second, referred to as *going for gold (GG),* emphasizes maximum adoption of advanced levels of implementation of 4R with reliance on enhanced efficiency fertilizers (Fig. 1.5; Table 1.4). *Strong foundation* projected 90% of fertilizer use would be under 4R practices by 2030 (90% total, delineated by 40% Basic; 30% Intermediate; 20% Advanced; only 10% of nitrogen use remains not under 4R management). *Going for gold* was considered to have a lower total adoption potential by 2030, projected at 70% of fertilizer under 4R practices use due to higher costs associated with advanced implementation, requiring more equipment and technology (70% total, delineated by 10% Basic; 10% Intermediate; 50% Advanced; 30% of nitrogen use remains not under 4R management).

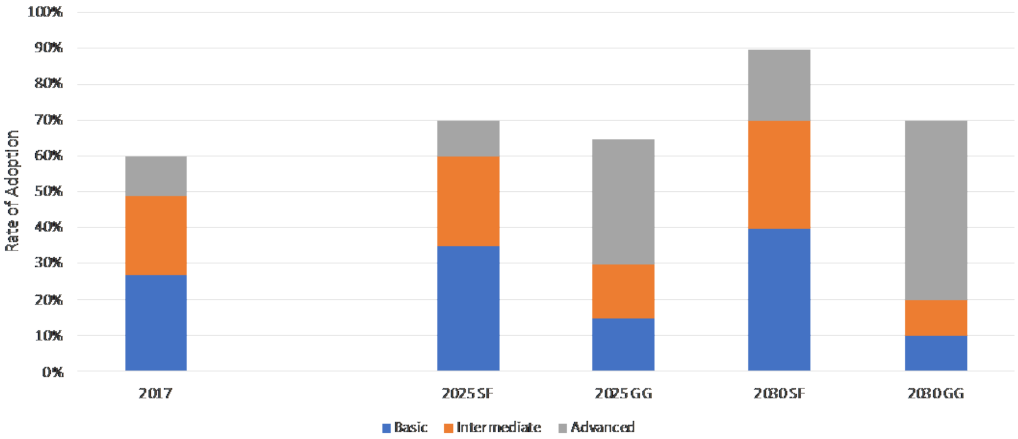

Figure 1.5: Rate of adoption scenarios for strong foundation (SF) and going for gold (GG) in 2025 and 2030 relative to estimated adoption levels in 2017 for corn.

The Importance of N Fertilizer Application Rate

When it comes to outcomes, the 4R N management practices emphasize both reducing N losses, particularly as N_2O, and increasing NUE. Reducing the total amount N fertilizer used has not often been emphasized as a critical outcome. However, Snyder (2017) provides a review of the benefits of 4R practices and highlights reduced N fertilizer rates as one. Numerous studies have identified the opportunity to reduce N fertilizer rates to reflect the increased efficiency of N fertilizer use. Venterea *et al.* (2016), in Minnesota, found that implementing 4R practices maintained corn yield with a 15% reduction in N fertilizer use. In a modelling study, Banger *et al.* (2020) estimated that with 4R practices, N fertilizer use in the corn growing area of Ontario could be reduced by up to 33%. Utilizing basic 4R implementation with lower N fertilizer rates result in corn yield was predicted to up to 10% higher yield than the use high rates of N fertilizer without 4R practices. There was no further increase in yield with more implementation of 4R beyond the basic level when the same fertilizer rate was used. Here we assumed no reduction in N rate for basic level of 4R implementation, 10% reduction of N rate for intermediate implementation, and 20% reduction in N rate associated with advanced implementation.

Reduction in Direct and In-direct N_2O Emissions Associated with Strong Foundation and Going for Gold Scenarios

The avoided N_2O emissions as a result of direct and indirect N_2O emissions, estimated using regional emissions coefficients based on soil landscape polygons, are reported for the *Strong Foundation* (Table 1.5) and *Going for Gold* (Table 1.6) scenarios.

The *Strong Foundation* scenario resulted in a total emissions reduction of 2,801kt CO_2e in 2025 and 3,261 kt CO_2e in 2030 (Table 1.5). The majority of this emissions reduction is a result of canola (1,305 kt CO_2e) and spring wheat (1,053 kt CO_2e) production on the Prairies and corn production in the rest of Canada (598 kt CO_2e). Potato production in all regions resulted in less than 1% of total N_2O emissions reductions due the smaller land base associated with potato production.

Table 1.5: Estimated direct and indirect N2O emissions reduction as a result of implementation of basic (B), intermediate (I), and advanced (A) 4R practices under the strong foundation scenario.

Strong Foundation (N_2O Reduction kt CO_2e)												
	2017				2025				2030			
	B	I	A	***Sum***	B	I	A	***Sum***	B	I	A	***Sum***
Corn												
Prairies	5	19	29	***53***	7	22	34	***63***	9	27	39	***75***
Rest of Canada	47	180	275	***502***	61	189	290	***541***	70	219	310	***598***
Winter Wheat												
Prairies	2	7	11	***20***	3	8	13	***24***	3	9	15	***28***
Rest of Canada	9	29	49	***87***	10	31	52	***94***	12	33	56	***101***
Spring Wheat												
Prairies	81	265	414	***759***	103	315	486	***904***	128	367	559	***1053***
Rest of Canada	4	13	21	***38***	5	14	22	***41***	5	16	24	***44***
Canola												
Prairies	150	286	485	***920***	128	391	564	***1082***	158	454	692	***1305***
Rest of Canada	2	4	7	***13***	2	5	7	***14***	2	6	8	***16***
Potato												
Prairies	1	2	4	***6***	1	2	4	***7***	1	3	5	***8***
Rest of Canada	1	10	18	***29***	1	11	19	***31***	2	11	20	***32***
Total Reductions	301	816	1311	***2428***	321	989	1491	***2801***	389	1144	1727	***3261***

The *Going for Gold* scenario resulted a similar level of emissions reductions as the *Strong Foundation* scenario, with a total emissions reduction of 2,895 kt CO_2e in 2025 and 3,253 kt CO_2e in 2030 (Table 5) as a result of the assumed lower overall adoption (70%) of this scenario resulting from the higher costs. The majority of this emissions reduction is a result of canola (1,306 kt CO_2e) and spring wheat (1,054 kt CO_2e) production on the Prairies and corn production in the rest of Canada (589 kt CO_2e). As with *Strong Foundation,* potato production in all regions resulted in less than 1% of total N_2O emissions reductions due the smaller land base associated with potato production.

Table 1.6: Estimated direct and indirect N2O emissions reduction as a result of implementation of basic (B), intermediate (I), and advanced (A) 4R practices under the going for gold scenario.

Going For Gold (N_2O Reduction kt CO_2e)												
	2017				2025				2030			
	B	I	A	Sum	B	I	A	Sum	B	I	A	Sum
Corn												
Prairies	5	19	29	53	3	19	42	64	2	18	53	73
Rest of Canada	47	180	275	502	26	160	368	554	17	145	426	589
Winter Wheat												
Prairies	2	7	11	20	1	7	16	24	1	7	20	28
Rest of Canada	9	29	49	87	4	27	63	95	3	24	72	100
Spring Wheat												
Prairies	81	265	414	759	44	268	608	920	32	264	758	1054
Rest of Canada	4	13	21	38	2	12	28	42	1	11	32	45
Canola												
Prairies	150	286	485	920	55	332	754	1141	40	327	939	1306
Rest of Canada	2	4	7	13	1	4	10	15	0	4	12	16
Potato												
Prairies	1	2	4	6	0	2	5	7	0	2	6	8
Rest of Canada	1	10	18	29	1	10	22	33	0	9	25	35
	301	816	1311	2428	138	840	1917	2895	97	813	2343	3253

In addition to N_2O emissions reduction associated with avoided direct and indirect N_2O emissions, there is also emission reductions associated with a reduction in the amount of fertilizer N required to be manufactured to support crop production. Nitrogen fertilizers have embodied fossil fuel emission of 4.05 kg CO_2 kg N^{-1} (Dyer et al., 2017). This would result in an additional 9% reduction in CO_2e for corn (32.8 kt CO_2e in 2030), 7% for winter wheat (7.3 kt CO_2e in 2030), 17% for canola (122.2 kt CO_2e in 2030) and 19% for spring wheat (109.0 kt CO_2e in 2030) for the *Strong Foundation* for a total reduction of (271.3 kt CO_2e in 2030). This would result in an addition 9% reduction in CO_2e for corn (82.1 kt CO_2e in 2030), 9% for winter wheat (18.2 kt CO_2e in 2030), 9% for canola (305.5 kt CO_2e in 2030) and 9% for spring wheat (272.4 kt CO_2e in 2030) for the *Going for Gold* for a total reduction of (687.2 kt CO_2e in 2030). This additional reduction in CO_2e has been included in the economic analysis of the cost per tonne of CO_2e.

Cost of 4R Adoption

The Economic Analysis Team (De Laporte et al. 2021) performed a detailed economic analysis of the costs associated with the implementation of both *Strong* Foundations and *Going for Gold* scenarios with the target adoption rates for 2025 and

2030 (De Laporte et al., 2021). A summary of these results is presented in Table 1.7. While the total emissions associated with the two scenarios are essentially the same, the costs are not. The *Going for Gold* scenario achieved its reductions at a much higher cost, \$109/t CO_2e in 2025 and \$193/t CO_2e in 2030 as compared to \$36/t CO_2e in 2025 and \$77/t CO_2e in 2030 under *Strong Foundation.* The difference in cost is primarily as a result of greater reliance of more costly practices such as increased reliance on enhanced efficiency fertilizers in the *Going for Gold* scenario. The emissions reductions were 2.5 to 3 times more expensive under the *Going for Gold* scenario. Note that it was assumed that a greater total adoption rate could be achieved by emphasizing broad adoption of basic and intermediate 4R (*Strong Foundation*) as opposed to an emphasis on advanced 4R (*Going for Gold*). This points to the cost effectiveness of emphasizing broad adoption of the more fundamental 4R practices of right rate (reduced N application rate), right time (split N application) and right place (variable in-field rates) over strategies that rely excessively on right product (enhanced efficiency fertilizers).

Table 1.7: Economic analysis of the adoption of strong foundation and going for gold scenarios in 2025 and 2030.

	Strong Foundation		**Going for Gold**	
	2025	2030	2025	2030
Adoption Inducement Cost (\$/ha)	\$7.93	\$16.41	\$29.41	\$58.91
Total Emissions Reduction (t CO2e)	2,919,111	3,513,944	3,224,365	3,761,948
Total Cost (\$)	104,756,333	271,124,391	352,164,267	725,546,456
Emissions Reduction Cost (\$/t CO2e)	\$36	\$77	\$109	\$193

Barriers to Adoption of 4R Practices

Nutrient management is already fundamental aspect of crop production so adoption of 4R principles is not a profound change to the cropping system management. Given the widespread availability of contract services and custom fertilizer applicators to deliver 4R implementation, there would relatively a relatively modest technological or expertise barrier to adoption. There may be a need for additional training and certification of agronomists to deliver these services but 4R management is rapidly becoming standard curriculum for certification processes for nutrient management planners and certified crop advisors. The financial resources for producers to engage independent agronomists may present an economic barrier.

There are additional measurements specific to nitrogen management that will add cost to 4R implementation. These include the measurement of the nitrogen supplying capacity of the soil and the amount of nitrate remaining in the soil following harvest. These practices are necessary for a measurement-based determination of the right rate of N fertilizer use in intermediate and advanced implementation of 4R N practices and the validation of the success of 4R implementation in reducing the potential for N loss. Soil nitrate measurements are not currently routinely done in all regions of Canada and the commercial laboratory capacity to conduct these measurements may need to be improved to ensure the success of the program. Despite the considerable amount of research that has been conducted in Canada (Zhang et al., 2002; Selles, et al., 1999; Sharifi et al., 2010; Dessureault-Rompre et al., 2011; Niyraneza et al., 2012; St Luce et al., 2012), there are few commercial soil test labs providing a measure soil N supplying capacity (N mineralization). There is a need to develop standardized approaches and the commercial laboratory capacity to conduct these measurements.

Documenting Success – Measuring Residual Soil Nitrogen

An important element of the adoption of a GHG mitigation program is to be able to document success – to track the implementation of the practice and document that the practice is resulting in the desired change. For agricultural GHG emissions this is difficult as the measurement of GHG emissions cannot be easily done on farm. Traditionally we have relied on documenting practice change and modelling the outcome in terms of GHG emissions. This is the basis of Canada's annual National Inventory Report on agricultural emissions to the UNFCCC. Currently that reporting does not consider the manner which N fertilizers are used and therefore would not reflect emissions reduction as a result of improved fertilizer management in any other way than in the reduction in the total amount of N fertilizer used (or a shift away from urea-based fertilizers).

To engage farmers in meaningful and long-lasting practice change it is important for them to be able to track progress on their own farm. This allows them to see the results of their actions and take ownership over the outcome. While on-farm GHG monitoring is not practical, the measurement of the amount of nitrate remaining in the soil following harvest, residual soil nitrogen is an option. The amount of nitrate remaining in the soil following harvest is not only a measure of the amount of nitrogen that was in excess of plant N requirements but is also a measure of the amount of nitrogen that is susceptible to loss as N_2O or potentially leached to groundwater resulting in impacts on water. It is important to note that the non-growing season is period of greatest N_2O emissions and leaching of NO_3^- to groundwater in Canada (Savard et al., 2007), and thus nitrate accumulating in the soil prior to this period has the greatest potential for loss and has no agronomic value. The agri-environmental indicator Residual Soil Nitrogen estimates the amount of nitrogen remaining in the soil after harvest as a mass balance between N inputs and N outputs. Measured values of this parameter would add precision to this indicator and would also improve our ability to estimate the potential for N_2O emissions and NO_3^- leaching in Canada.

Measuring soil nitrate concentration to a depth of 60 cm in the fall immediately after harvest is essential to inform and document the success of 4R implementation in improving the efficiency of nitrogen use and reducing N_2O emissions. The cost of the collection and analysis of the samples could represent a barrier to adoption of improved nitrogen management. Since year-to-year variation in climatic factors can influence the magnitude of residual soil nitrate it should be measured annually but should be evaluated over a number of years to account for year-to-year variation. The value of RSN should be provided to the producer so that they can track their operation's success in increasing nitrogen use efficiency and reducing the potential for N loss. The national reporting of these numbers could also provide valuable input in refining the Residual Soil Nitrogen agri-environmental indicator. Support for independent agronomist could facilitate the collection of soil samples and documentation of changes in soil nitrate remaining in the fall.

Co-benefits of 4R Adoption

Positive

It is important to recognize that improved N management practices also result in significant co-benefits related to reduce N losses. This includes reduced NH_3 volatilization, which can have adverse impacts on surrounding ecosystems, and reduced NO_3^- leaching to groundwater which is a major concern in a number of provinces.

Ammonia volatilization is primarily the result of ammonia-based N fertilizers and manures being left on the soil surface, exposed to the atmosphere. 4R practices that delay the rate of ammonia formation (urease inhibitors) or place the N source in the soil (right place) can reduce these emissions. Practices which delay the conversion of NH_3 to NO_3^- can increase the potential for NH_3 emissions and raise the potential "pollution swapping" (Drury et al., 2017). The distribution of NH_3 emissions from fertilizer (Fig. 1.5) reflects the use of higher rates of ammonium-base N fertilizers and animal manures in agriculture, with greatest emissions in Eastern Canada.

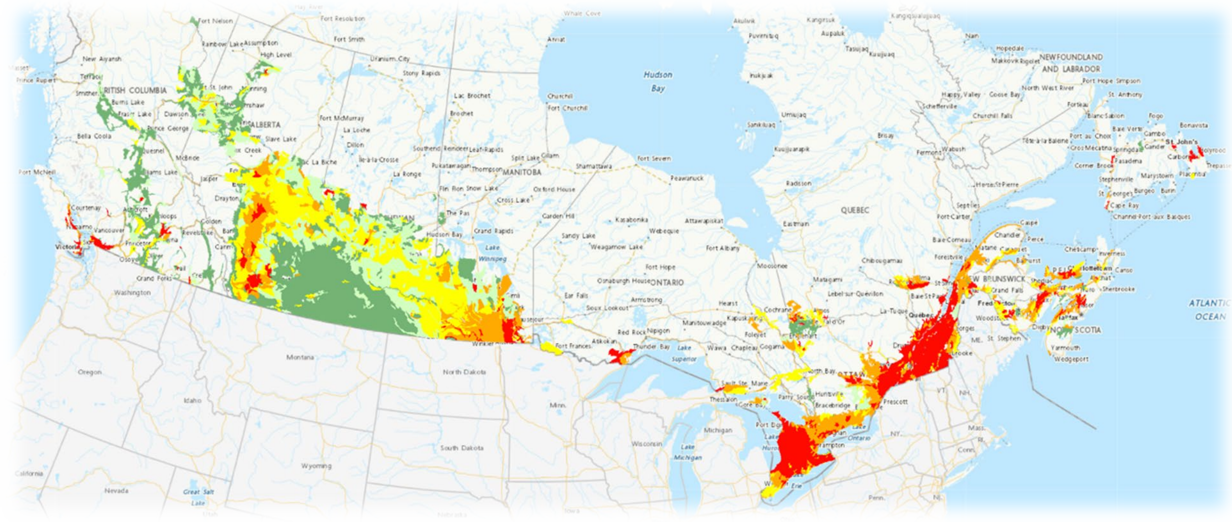

Figure 1.6: Ammonia emissions from agriculture[3].

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[3] Source : https://open.canada.ca/data/en/fgpv_vpgf/cc0aadbf-f5e6-41f2-8877-84469bb76076

Another important impact of N use in agriculture is the increased potential for NO_3^- leaching to groundwater. In more humid regions of Canada, where annual precipitation exceeds annual evapotranspiration there is annual recharge of groundwater sources, primarily during the non-growing season. This recharge of groundwater also has the potential to carry contaminants to the groundwater should they be allowed to accumulate in the soil prior to periods of recharge. Thus, the potential for NO_3^- contamination of groundwater is a product of the timing of the recharge of groundwater and the timing and magnitude of NO_3^- accumulation in the soil. The Agri-Environmental Indicator of the Risk of Water Contamination by Nitrogen (Fig. 1.6) represents the potential for excess nitrogen to impact water. Its calculation is based, in part, on an estimation of Residual Soil Nitrogen, the difference between estimated N inputs and N outputs.

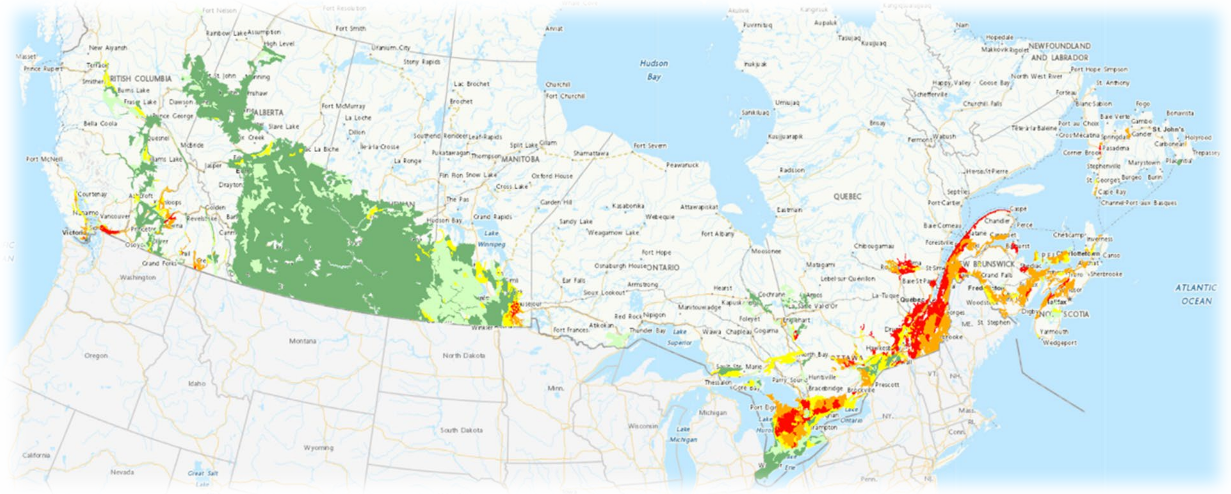

Figure 1.7: Risk of water contamination by nitrogen[4]*.*

Limitations and Additional Opportunities Beyond the Scope of this Report

It is important to note that this analysis was intentionally limited to practices that were currently well documented and could be implemented immediately. There are a number of limitations to our analysis, and also additional opportunities that could be considered in future analyses that fell beyond the scope of this work.

- Potato production – While we have estimated the potential N2O emissions reductions associated with improved nitrogen management, these estimates have a high degree of uncertainty. In addition, because of the relatively small area under potato production the emissions reductions represent a small percentage of the total potential reductions. As a result, we did not undertake a costing of these measures at this time.
- Barley production – There were 2.1 million ha in barley production in Canada in 2017 using 163 million kg of N fertilizer. An initial analysis suggested that 340 kt CO_2e in direct and indirect N_2O emissions could be avoided each year

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[4] https://open.canada.ca/data/en/fgpv_vpgf/8f96099a-cb27-45fb-986b-5fdb5f3b1828

by 2030 through the adoption of 4R practices similar to those presented in this report. Further there could be an additional 55 kt CO_2e reduction associated with reduced N fertilizer manufacture associated with reduced N fertilizer requirements associated with 4R adoption. There is a lack of date on the potential for N_2O emissions reduction in barley production and the cost associated with implementing 4R practices in this crop to make a more definitive statement as to the emissions reduction potential.

- Measurement of soil nitrogen supplying capacity of Canadian agricultural soils – One of the greatest challenges to improved nitrogen management is determining the right rate of fertilizer N addition. To effectively determine the need for supplemental nitrogen, it is important to accurately assess all N sources. The nitrogen supplying capacity of the soil varies significantly between regions, within a field, and as a result of cropping system and management practices. There is no accepted means of measuring the nitrogen supplying capacity of the soil and including this information in the determination of the requirement for supplemental nitrogen. Over the past several decades multiple researchers across the country have been working on the methods to measure nitrogen supplying capacity of nitrogen mineralization (Zhang et al., 2002; Selles, et al., 1999; Sharifi et al., 2010; Dessureault-Rompré et al., 2011; Niyraneza et al., 2012; St Luce et al., 2012), but these methods have not found their way into common practice yet. There is a need to adopt site-specific measures of soil N supplying capacity as part of routine soil testing and use these results in determining the need for supplemental N additions. This requires investment that translates our current scientific understanding of the measurement of N mineralization into commercially available soil testing processes. Living Labs Atlantic and the Prince Edward Island Department of Agricultural and Land has been evaluating an approach to achieving this by the inclusion of a measure of biologically available nitrogen as part of their soil health testing pilot, but the results are not ready yet.
- Manure management – Improved management of the N contained in manure could also result in significant N_2O emissions reductions. The 2017 Farm Environmental Management survey estimated there were 330 million kg of available N associated with animal manure. According to surveys conducted by Stratus for Fertilizer Canada, much of this manure is applied in the fall. According to Statistics Canada[5], in 2016 only about 60% of farms injected or incorporated manure following application. In the 2004 Farm Environmental Management Survey, only 43.7% of farmers indicated they reduce fertilizer application rates on fields which had received manure. There is an opportunity to improve the efficiency of the use of manure through more quantitative and uniform application of manure and through better budgeting for manure nitrogen additions resulting in a reduction in N fertilizer application.

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[5] https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210041001

- Increased production of grain legumes replacing non-legume grains – The replacement of non-legume grains, largely used to feed livestock, with grain legumes would result in a reduction in the amount of N fertilizer used. This represents a complex transition in both the emissions associated with crop production as well as the impact on global grain markets and the food production system. The trend towards greater reliance on plant-based protein in human diets may drive this transition. The assessment of the potential for replacement of non-legume grains with grain legumes merits additional.

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2. Cover Crops for Climate Change Mitigation in Canada

Introduction

For this analysis, a cover crop was defined as a non-harvested crop grown in addition to normal production of a harvested cash crop. Cover crops build soil organic matter, improve soil structure, increase soil microbial diversity, protect the soil from erosion, reduce nitrogen leaching, and reduce the need for nitrogen fertilizer via biological nitrogen fixation where legumes are included in the cover crop. Other benefits include reducing pests, weeds, and diseases that impact the success of harvested cash crops.

Farmers generally report that the benefits associated with cover crops, including improved soil resilience to various stresses, reduced loss of soil nutrients from soil erosion and leaching, reduced need for extra tillage to repair channeling from soil erosion, improved soil biological health that supports soil structure and nutrient cycling, and/or reduced costs associated with the management of weeds, diseases, and/or pests, are at least sufficient to cover seeding costs (Bergtold et al., 2017; Roesch-McNally et al., 2018). The private benefits of cover cropping have been reported to be as high as \$600 ha^{-1} yr^{-1} in the case of seed corn in southern Ontario (O'Reilly et al. (2011). However, based on a survey of farmers across the US, many of these soil benefits described above only increase over time while some benefits only occur periodically depending on conditions. Therefore, it may take 3 years to cover seeding costs and 5 years of continual cover cropping to ensure that total benefits exceed annual costs of cover cropping (Myers et al. 2019). However, it must be noted that the magnitudes of private benefits accrued likely varies significantly by region, which will greatly affect adoption by region. More research is needed on the short- and long-term benefits of cover crops to improve our understanding of this practice.

Based on the 2017 Farm Management Survey (D. Cerkowniak, AAFC, personal communication), for this analysis we estimated that there are currently 630,000 ha of cover crops, ranging from 13.5% of cropland in the Mixed Wood Plains to 0.4% in the Black soil zone of the Prairie (data not shown).

Cover crops are either interseeded (planted within) a cash crop or seeded after cash crop harvest. The cover crop growth continues after cash crop harvest for the fall, or, for a winter cover crop, continues to grow the next spring before the next cash crop is grown. Particularly for later-harvested crops, rather than trying to seed post-harvest for emergence that fall, the cover crop can be seeded later into frozen ground so that it germinates and grows in the following spring before the next cash crop. Where the normal production practice is to fallow the land by not growing a crop in the normal growing season, a cover crop grown on fallow land is a good option to provide many soil benefits.

Forages established within or immediately after a cash crop are not considered cover crops when the forage grows for one or more subsequent growing seasons. The practice of interseeding forages with a cash crop, often called companion cropping, is already considered a normal practice for forage establishment. Forage crops provide many soil and environmental benefits, but these are due to the forage production over years, not to the interseeding during the establishment year. An intercrop, when two or more crop types are grown together but all harvested for grain, was also not considered to be a cover crop. Winter cereals grown for grain harvest provide some of the benefits of the cover crop in terms of reducing nitrate leaching and protecting the soil from erosion in the fall, winter, and early spring, but are not additional to normal production so are not considered cover crops.

There are many species options for cover crops including grasses (winter cereals such as wheat and rye, spring cereals such as oat or barley, forage grasses such a ryegrasses), legumes (alfalfa, vetch, clover, pea, soybean) and non-legume broadleaves (radish, buckwheat, marigold). An increasing practice is to have a mix of species and types to both better capture the various benefits provided by each and to ensure some species thrive no matter the weather conditions.

Methods for Estimating Greenhouse Gas Emissions and Carbon Sequestration

Cover Crop Adoption

Potential Adoption

In Canada generally, fall conditions can limit cover crop adoption due to insufficient warmth, suboptimal soil moisture for successful growth, and time conflicts with cash crop harvest. For these reasons, a previous cash crop that matures early and/or are suitable for interseeded cover crops (e.g., winter cereals) have much more potential to be technically feasible for adoption than later maturing cover crops and/or cash crops that require post-harvest seeding (e.g., potato) as the latter is more likely to conflict with harvest of other cash crops. Favourable spring conditions for cover crops depend on the type and/or proportion of subsequent cash crops that will be seeded relatively late in the normal spring seeding window to allow time for appreciable spring growth of winter cover crops and, in drier climates, opportunity for spring precipitation to replenish surface soil moisture after spring termination of winter or early spring cover crops. Time constraints for seeding cover crops post-harvest were estimated to increase with later harvest, especially for crops for which interseeding is not feasible because the harvest of the previous cash crop would deleteriously affect an interseeded cover crop (e.g., potato) or the interseeded cover crop could deleteriously affect the harvest of the cash crop (e.g., lentil). We assumed farmers would adopt cover crops only for the subset of their fields that have the most favorable conditions in any specific year for successful cover crop production (e.g., timing of cover crop seeding opportunity, soil tractability for seeding, subsequent cash crop well-suited to the prior cover crop). Those fields with unfavourable conditions were assumed to not have practical potential for adoption.

Therefore, there was a maximum potential adoption assigned by climate zone (zone is the LULUCF reporting zone in ECCC (2019) except the soil zone (Government of Canada, 2013) in the Boreal Plain and Prairie reporting zones) and previous cash crop (Table 2.1). These potential adoption rates need to be viewed as long-term, regional rates and would not apply on local, annual basis. If conditions are especially unfavourable for an area in one year, there may be no potential adoption in that year and area whereas, in another year that same area may have especially favourable conditions and adoption could exceed the long-term potential. Where the climate is favourable for cover crops such as the mixed wood plains of southern Ontario and Southern Quebec, the potential subset of fields for cover crops would be the majority of fields whereas, where the climate is more unfavourable for cover crops (such as the Brown soil zone of the Saskatchewan and Alberta), that subset of potential fields would only be about ½ of all fields. Across Canada, the potential land available for cover crops was 20.5 million ha, or 63% of all land used for annual crops.

Table 2.1: Maximum feasible adoption rate by zone and previous cash crop.

	Previous Cash Crop							
Zone	Winter wheat, fall rye[1], winter canola	Pea	Barley, oat, mustard	Fallow replacement	potato, sugar beet, chickpea	Grain corn, sunflower	bean, flax, lentil	Spring canola, spring rye[1], silage corn, canary seed, spring wheat[2], soybean
	Maximum Potential Adoption (% of crop area)							
Atlantic Maritime	95	85	90	100	30	70	80	85
Mixed Wood Plains	100	95	90	100	30	70	80	85
Boreal Shield East	85	70	80	100	10	20	40	60
Boreal Shield West	85	70	80	100	20	20	50	70
Brown soil	80	60	70	100	5	20	40	50
Dark Brown soil	80	60	70	100	10	20	50	60
Black soil & Montane Cordillera	90	80	85	100	10	40	50	75
Dark Gray soil	85	70	80	100	10	30	40	50
Gray soil	80	60	70	100	5	20	40	50
Pacific Maritime	100	95	90	100	70	80	80	85

[1] includes triticale, [2] includes durum

Research and development that selects and breeds for cover crop species and cultivar that are well adapted to local conditions will make cover crop adoption more attractive. Breeding and selection for cover crop cultivars having prolific seed production, small seeds, and good ability to establish in poor seedbed conditions will also improve adoption but reducing cover crop seed costs.

Estimated Actual Adoption

The primary barriers to using cover crops are the uncertainty of the magnitude of economic benefits for the cash crop production relative to the cost of seed and for seeding cover crop, the expenses for cover crops occurring before returns, labour and equipment constraints for seeding cover crops, and the risk that cover crops do not perform as well expected to due unexpected conditions such as poor cover crop establishment or destructive weather after establishment. The expected risks from poor cover crop performance are considered included in potential adoption.

The potential adoption also decreases as the potential biomass production of the cover crop decreases (described under greenhouse gas effects following) since that reduces the various greenhouse gas and agronomic benefits of cover crops. Those reduced benefits then reduce the attractiveness of adoption. Of course, the farmer's perception of the benefit and cost of cover crops will also affect willingness to adopt – some farmers will perceive greater benefits and be more motivated to adopt cover crops even in less favourable cash-crop-zone combinations.

Potential Adoption by 2030

We assumed that by 2030 techniques for successfully seeding cover crop within or after cash crops are established and services for that seeding is available on a contract basis so every producer can use cover crops if they desire, albeit at a cost. Under these assumptions, the primary barriers are the perceived likelihood that the benefits of cover crops will be less than their costs both in the short term and long term. Our analysis demonstrated that the amount of adoption will depend on the external payments to induce adoption and the value farmers place on non-N benefits proved by cover crops. The most aggressive scenario for adoption investigated would have cover crops on 90% of the land potentially available for cover crops, encompassing 46 million acres.

Effects on Greenhouse Gas Emissions

Carbon Sequestration

For this analysis, the benefits of cover crops were assumed to be closely related to the biomass produced by the cover crop. This is because the cover crop biomass affects total uptake of soil nutrition, the amount of root growth that affects the soil structure and soil microbial community, the amount of C input to the soil, and the amount of growth promoting substances or disease/pest suppression provided by the cover crop. The cover crop biomass varies depending on the expected cash crop harvest date and/or the suitability of interseeding of the previous cash crop, meaning that the potential benefits and feasibility of cover crops vary by climate zone and the type of previous cash crop.

Much of Canada's agricultural land is on the prairies and, since this region is climatically more difficult for cover crops generally speaking, we established a relatively fine division of agroclimates to better capture the effect of agroclimatic differences within this region (Fig. 2.1).

Cover crops mitigate GHG emissions through increased C sequestration (Abdalla et al., 2019; Bai et al., 2019). We based our rates on a modification of C sequestration rates of global meta-analysis mean value of 0.32 Mg C ha^{-1} (Poeplau and Don, 2015) which is within the range of measured C sequestration rates for the Mixed Wood Plains zone: no effect (Jarecki et al., 2018; N'Dayegamiye and Tran, 2001), 0.24 Mg C ha^{-1} yr^{-1}(Agomoh et al., 2020), and 0.67 Mg C ha^{-1} yr^{-1} (Yang and Kay, 2001). Poeplau et al. (2015) found a rate of 0.27 Mg C ha^{-1} yr^{-1} in a similar climate to the Mixed Wood Plains in S. Sweden. Soil sequestration rates were then adjusted for soil zones based on limited evidence: 0.49 Mg C ha^{-1} yr^{-1} for climate similar to Pacific maritime (Poeplau et al. 2015) and 0.2 Mg C ha^{-1} (Campbell et al., 2007) to 0.32 Mg ha^{-1} (Biederbeck et al., 1998) for cover crop as fallow replacement in the Brown soil zone.

To estimate the sequestration rates for associated cash crops and other zones, the carbon sequestration rates were estimated based on the ratio of estimated cover crop C input relative to 1.87 Mg C ha^{-1} yr^{-1} for the soil C sequestration rate of 0.32 Mg C ha^{-1} yr^{-1} soil. The expected growth of the cover crop is dependent on timing of the harvest of the previous cash crop; the earlier the previous cash crop is harvested, the greater the expected growth of cover crop. This translates into an estimated input of 1.27 Mg C ha^{-1} yr^{-1} for clover when interseeded into spring wheat and 0.31 Mg C ha^{-1} yr^{-1} when clover is interseeded into later maturing corn (N'Dayegamiye et al., 2015). In order to consider soil zones, the C input from cover crops in Black soil zone were estimated to be about 0.5 to 0.6 Mg C ha^{-1} yr^{-1} (based on cover biomass yields) (Martens et al., 2001; Thiessen-Martens et al., 2015) and in the Dark Brown soils C input from cover crops were estimated to range from near 0 in dry years to 0.3 Mg ha^{-1} yr^{-1} in moister years (Blackshaw et al., 2010).

C sequestration rates for other soil zones and previous cash crops were estimated by interpolation and extrapolation from these values by expert opinion, and dependent on climate considerations and the characteristics of previous cash crop. The most favourable climate for cover crop in Canada is the Pacific Maritime followed by the Mixed Wood Plains and Atlantic Maritime, which were assumed to have one-half the growth potential for cover crops (Table 2.2). The Black soil is the most favourable climate for the Prairies but both cold and lack of water were assumed to restrict the growth of cover crops by about one-half compared to the Mixed Wood Plains. Within the Prairies, cover crop potential becomes increasingly restricted by cold moving from Black to Dark Gray and then to rates of one-half those of the Black soil zone in the Gray soil zone and by lack of water moving from the Black to Dark Brown down to rates about 20% of the Black soil zone in the Brown soil zone. Montane Cordilleran and Boreal Shield zones were considered similar overall to the Black soil zone albeit ignoring the significant variation in climate in those zones, particularly the Montane Cordilleran, that would affect the ratings on a local area basis. In selecting these average rates, we assumed that practices that greatly increase risk of having an unsuccessful cover crop, such as seeding the cover crop into dry soil after an unplanned late harvest of the previous cash crop, were already reflected in potential adoption rate for each climate-cash crop combination, i.e., where risk of poor cover crop growth is higher, then those situations of high risk are avoided for cover crops so that the potential adoption rate is lower. Hence, the average sequestration rates were assumed for generally favourable situations for cover crop production and not lowered by the foreseeable particularly unfavourable conditions for cover crop production that occur within each climate-cash crop combination.

Although there is a trend for legume cover crops to produce lower Soil Organic Carbon increases than non-legume cover crops (Abdalla et al., 2019; Poeplau and Don, 2015), the difference was not significant, so we assumed no effect of the cover crop type mix. We also assumed the linear C sequestration rate right to 2050 as Poeplau and Don (2015) suggest their C linear sequestration rate may be valid for up to 53 years and because of limitations on potential adoption, cover crops would not be used every year.

Some producers, particularly organic producers, may grow an unharvested crop, that may be termed a cover crop, for soil improvement instead of a cash crop. These crops are also called green manure crops. For a green manure cover crop grown on planned fallow in semiarid areas, the carbon sequestration benefits are about the same as growing a cash crop instead of fallow (Campbell et al. 2007). Therefore, there is no SOC benefit to green manure crops rather than a cash crop in semiarid region. The GHG effects for this practice of growing a cover crop instead of a cash crop are not sufficiently studied in more productive climates to estimate the C sequestration. The economics of growing a cover crop instead of a non-organic cash crop in productive environments also needs to be considered.

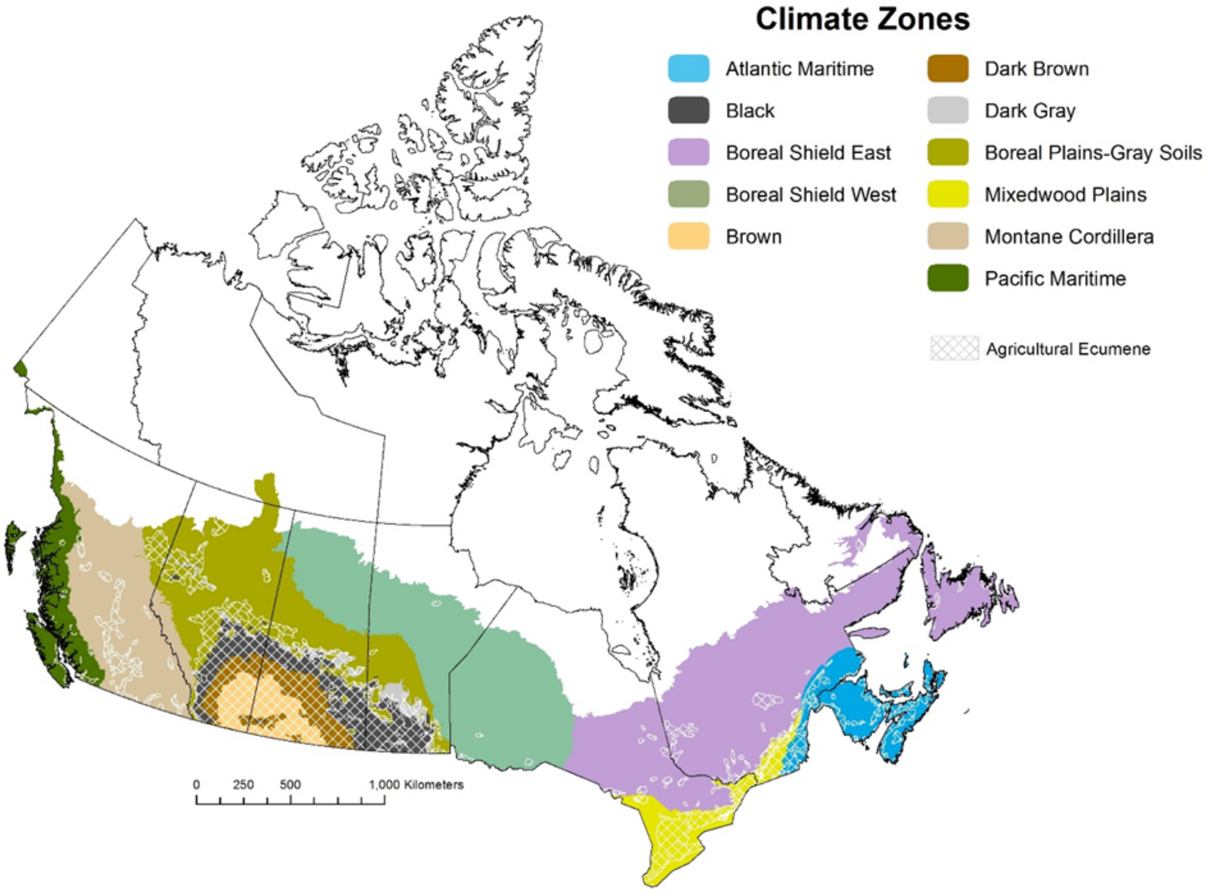

Figure 2.1: Climate zones used for cover crop analysis.

Table 2.2: Soil carbon sequestration rate(CCseq) by climate zone and cash crop

	Previous Cash Crop							
Zone	Winter wheat, fall rye[1], winter canola	Pea	Barley, oat, mustard	Fallow replacement	potato, sugar beet, chickpea	Grain corn, sunflower	bean, flax, lentil	Spring canola, spring rye[1], silage corn, canaryseed,spring wheat[2], soybean
	C change rate (Mg C ha^{-1} yr^{-1})							
Atlantic Maritime	0.32	0.26	0.29	0.64	0.13	0.19	0.16	0.22
Mixed Wood Plains	0.32	0.26	0.29	0.64	0.13	0.19	0.16	0.22
Boreal Shield East	0.16	0.13	0.14	0.48	0.06	0.10	0.08	0.11
Boreal Shield West	0.13	0.10	0.12	0.45	0.05	0.08	0.064	0.09
Brown soil	0.06	0.05	0.06	0.26	0.03	0.04	0.03	0.05
Dark Brown soil	0.10	0.08	0.09	0.29	0.04	0.06	0.05	0.07
Black soil & Montane Cordillera	0.16	0.13	0.14	0.48	0.06	0.10	0.08	0.11
Dark Gray soil	0.13	0.10	0.12	0.38	0.05	0.08	0.06	0.09
Gray soil	0.08	0.06	0.07	0.32	0.03	0.05	0.04	0.06
Pacific Maritime	0.64	0.51	0.58	0.64	0.26	0.40	0.32	0.45

[1] includes triticale, [2] includes durum

Nitrous Oxide Emission

Based on meta-analyses (Abdalla et al., 2019; Basche et al., 2014; Han et al., 2017; Muhammad et al., 2019; Poeplau and Don, 2015), we estimated that non-legume cover crops reduce annual direct N_2O emissions in cold climates (Muhammad *et al.*, 2019) while they increase direct N_2O emissions with legume cover crops. The latter is consistent with the only comparison we found for Canada (Quesnel et al., 2019). The effect was assumed to be 10% increase or decrease dependent on the fraction of legume biomass in the cover crop:

$$FdN_2O = 0.9+Pleg*0.2$$

where FdN_2O, is non-dimensional factor for cover crop effects on direct N_2O emissions estimated by the methods of Rochette et al. (2008) as implemented by ECCC (2019) and Pleg is the fraction of legumes for whole cover crops area in a SLC polygon. The effect of cover crops on direct N_2O emission are provided in Table 2.3.

Compared to no cover crops, cover crops significantly reduce nitrate leaching (Thapa et al., 2018) with reducting increasing linearly to estimated biomass C input of about 1.87 Mg C ha^{-1} yr^{-1}. Abdalla *et al.* (2019) found that non-legume cover crops led to about 50% reduced leaching and about 30% reduced leaching for legume cover crops. Using the latter rates, and scaling the reduction by the cover crop C sequestration (CCseq) (Table 1), the effect was estimated as:

$$\text{Fleach} = 1\text{-min}\ [1, \text{CCseq}\ (\text{Mg ha}^{-1}\ \text{yr}^{-1})/0.32\ (\text{Mg ha}^{-1}\ \text{yr}^{-1})] * (0.5\text{-Pleg} * 0.2)$$

where Fleach is the dimensionless leaching reduction factor applied to estimated N leaching and subsequent indirect N_2O emission as calculated using method of Rochette et al. (2008) as implemented by ECCC (2019) and Pleg is the fraction of legume biomass in the cover crop. Table 2.4 provides the effect of cover crops on avoided N leaching. The avoided leached N was assumed to be cycled through the cover crop and then available to the next cash crop.

Table 2.3: Estimated effects of cover crops on change in direct N_2O emissions (negative is a reduction). Values are for 100% legumes. Multiply value by (-1 +(fraction of legume species biomass in mix)/0.5) to estimate for other mixes (e.g., if 25% of biomass is l legumes multiply by -1 +0.25/0.5=-0.5, note, the negative sign turns reduction to an increase).

	Previous Cash Crop							
Zone	Winter wheat, fall rye[1], winter canola	Pea	Barley, oat, mustard	Fallow replacement	potato, sugar beet, chickpea	Grain corn, sunflower	bean, flax, lentil	Spring canola, spring rye[1], silage corn, canaryseed,spring wheat[2], soybean
	N_2O emissions change (kg N_2O ha^{-1} yr^{-1})							
Atlantic Maritime	-0.92	-1.11	-0.92	-2.53	-1.02	-1.03	-1.07	-0.91
Mixed Wood Plains	-0.41	-0.49	-0.52	-0.47	-0.52	-0.46	-0.44	-0.44
Boreal Shield East	-0.67	-0.57	-0.95	-1.14	-1.33	-0.70	-0.54	-0.65
Boreal Shield West	-0.96	-1.16	-1.21	-2.20	-1.26	-1.08	-1.02	-1.10
Brown soil	-0.10	-0.09	-0.10	-0.10	-0.10	-0.17	-0.08	-0.09
Dark Brown soil	-0.12	-0.12	-0.12	-0.11	-0.11	-0.12	-0.10	-0.11
Black soil	-0.18	-0.17	-0.17	-0.16	-0.19	-0.21	-0.16	-0.17
Dark Gray soil	-0.26	-0.21	-0.22	-0.23	-0.24	-0.29	-0.20	-0.21
Gray soil	-0.34	-0.26	-0.33	-0.30	-0.34	-0.34	-0.23	-0.26
Montane Cordillera	-1.10	-1.27	-1.86	-4.11	-6.32	--1.02	-1.12	-1.13
Pacific Maritime	1.84	0.89	1.37	5.04	2.01	2.70	2.91	1.61

Table 2.4: Estimated effects of cover crops on N retained from leaching. Values are for equal mix of legume and non-legume cover crop species, if all non-legume species then multiply values by 1.67, if all legume species, multiply by 0.6.

	---------- Previous Cash Crop ----------							
Zone	Winter wheat, fall rye[1], winter canola	Pea	Barley, oat, mustard	Fallow replacement	potato, sugar beet, chickpea	Grain corn, sunflower	bean, flax, lentil	Spring canola, spring rye[1], silage corn, canary seed, spring wheat[2], soybean
	---------- N recovered from leaching (kg N ha^{-1} yr^{-1}) ----------							
Atlantic Maritime	13.3	8.8	9.6	17.7	4.6	8.3	6.9	8.7
Mixed Wood Plains	11.6	10.2	10.7	11.7	5.6	7.6	6.2	8.4
Boreal Shield East	3.3	1.5	3.5	8.1	1.4	2.6	1.4	2.6
Boreal Shield West	4.4	3.7	4.0	9.2	2.5	2.7	2.4	3.0
Brown soil	0.6	0.4	0.5	2.2	0.2	0.4	0.3	0.4
Dark Brown soil	1.4	1.1	1.3	4.0	0.5	0.9	0.6	1.0
Black soil	4.1	3.1	3.6	7.6	2.0	2.8	1.9	2.9
Dark Gray soil	4.2	2.9	3.4	9.3	1.8	2.7	1.9	2.7
Gray soil	2.2	1.6	1.9	8.4	1.0	1.5	1.1	1.5
Montane Cordillera	3.2	2.8	3.7	8.1	1.1	1.4	1.6	2.1
Pacific Maritime	19.5	21.0	20.1	18.1	8.9	13.4	12.5	18.9

Table 2.5: Estimated effects of cover crops on indirect N2O emissions (negative indicates a reduction). Values are for 100% legume. Multiply value by 0.67 (1-fraction of legume species in mix) +1 to estimate for other mixes (e.g., if 50% of biomass is legumes, multiply by 0.67*0.5 +1=1.34).*

	Previous Cash Crop							
Zone	Winter wheat, fall rye[1], winter canola	Pea	Barley, oat, mustard	Fallow replacement	potato, sugar beet, chickpea	Grain corn, sunflower	bean, flax, lentil	Spring canola, spring rye[1], silage corn, canary seed, spring wheat[2], soybean
	N_2O emissions credit (kg N_2O ha^{-1} yr^{-1})							
Atlantic Maritime	-0.40	-0.46	-0.39	-1.06	-0.44	-0.44	-0.43	-0.39
Mixed Wood Plains	-0.16	-0.19	-0.20	-0.18	-0.20	-0.18	-0.17	-0.17
Boreal Shield East	-0.28	-0.23	-0.37	-0.47	-0.55	-0.29	-0.22	-0.26
Boreal Shield West	-0.38	-0.45	-0.47	-0.86	-0.50	-0.42	-0.41	-0.43
Brown soil	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
Dark Brown soil	-0.05	-0.06	-0.06	-0.06	-0.05	-0.06	-0.05	-0.06
Black soil	-0.09	-0.08	-0.09	-0.08	-0.10	-0.10	-0.08	-0.09
Dark Gray soil	-0.13	-0.10	-0.11	-0.12	-0.12	-0.14	-0.10	-0.11
Gray soil	-0.15	-0.12	-0.15	-0.14	-0.15	-0.15	-0.11	-0.12
Montane Cordillera	-0.28	-0.41	-0.59	-0.99	-0.97	-0.18	-0.31	-0.26
Pacific Maritime	-0.75	-0.36	-0.54	-1.95	-0.81	-1.11	-1.18	-0.66

N Provided by Legumes in Cover Crops

The estimated N credit from productive legume cover crops in Ontario is 45 kg ha^{-1} for the following crop, but it is 80 kg ha^{-1} if the following crop is corn (OMAFRA, 2020). We also assumed that Ontario rates apply to a CCseq (Table 2.1) of 0.32 Mg ha^{-1} yr^{-1} for a cover crop legume fraction of 1 and decreases linearly with that latter fraction. Thus, the N credit for cover crops, CCN (kg ha^{-1}) was:

$$CCN = CCseq\ (Mg\ ha^{-1})/0.32\ (Mg\ ha^{-1}) * Pleg * (45 + Pcorn*35)\ (kg\ N\ ha^{-1})$$

where Pcorn is the fraction of grain and silage corn in the SLC polygon. We also added to the N credit the estimated reduction in N leaching due to non-legume cover crops, assuming that N would be recovered by the subsequent cash crop. Table 2.6 provides estimates of the N credit from legumes in cover crops.

Table 2.6: Estimated effects of cover crops on N credit from legumes. Values are for 100% legume. Multiply value by fraction of legume species in mix to estimate for other mixes (e.g., if 50% of biomass is legumes, multiply by 0.5).

	Previous Cash Crop							
Zone	Winter wheat, fall rye[1], winter canola	Pea	Barley, oat, mustard	Fallow replacement	potato, sugar beet, chickpea	Grain corn, sunflower	bean, flax, lentil	Spring canola, spring rye[1], silage corn, canaryseed,spring wheat[2], soybean
	N credit (kg N ha^{-1} yr^{-1})							
Atlantic Maritime	51.5	33.9	39.9	109.3	7.7	24.2	20.4	31.5
Mixed Wood Plains	52.4	39.0	45.3	112.0	4.6	24.5	22.7	33.7
Boreal Shield East	20.3	13.0	16.8	71.2	0.5	3.0	4.7	8.3
Boreal Shield West	16.6	10.5	14.0	67.7	0.4	2.3	4.0	6.8
Brown soil	7.3	4.3	5.7	36.1	0.2	1.1	1.8	3.2
Dark Brown soil	10.9	6.5	8.5	40.7	0.3	1.6	2.7	4.7
Black soil	20.6	14.5	17.3	67.9	0.9	4.2	5.7	9.5
Dark Gray soil	15.7	10.1	13.0	54.3	0.4	2.3	3.6	6.3
Gray soil	9.1	5.4	7.1	45.2	0.2	1.4	2.3	4.0
Montane Cordillera	24.1	15.3	18.1	72.0	1.0	4.8	6.7	11.1
Pacific Maritime	128.8	80.2	89.0	114.9	9.4	48.6	42.5	75.9

Effect of Grazing and Harvest of Cover Crops

Grazing cover crops can provide important economic benefit for producers (Thiessen-Martens and Entz, 2011). There is little information on how grazing affects the GHG balance. Assuming that grazing decreases total growth by 20%, grazing removes 70% of above ground growth with 80% digestibility, and a root:shoot ratio for cover crop of 0.2 in upper 30 cm of soil (Hu et al., 2018), the grazing would reduce the C returned to the soil by about 50%. The effect of grazing on N leaching of a cover crop is more complicated but, to be conservative, we assumed that 50% of N that would have been prevented from leaching by the cover crop did not occur due to reduced growth of the cover crop from grazing and a return of readily leachable N in grazing livestock urine. Based on two recent studies (Abagandura et al., 2019; Singh et al., 2020), we assumed that grazing of cover crops had no effect on direct N_2O emissions from the soil. The indirect GHG effects of the new feed from cover crop is complex. Assuming the livestock numbers are not affected, that displaced feeds had similar diet quality, and the displacing of feed by cover crops does not increase GHG emissions elsewhere, the simplest assumption is that there is there is no additional change in GHG emissions from livestock or the land due to grazing cover crops beyond the direct effects on C sequestration and N leaching from grazed cover crops described earlier. At this point there is insufficient data to estimate how a cover crop, whether a conventional cover crop that is additional to cash crop or a green-manure cover crop is harvested mechanically for forage affects SOC change and N_2O emissions.

Other Emissions

There are additional emissions associated with implementing cover crops. We estimated 15 kg CO_2e ha^{-1} as the fossil fuel emissions from shallow soil disturbance for the seeding (Dyer and Desjardins, 2003). We also used 91 CO_2e ha^{-1} for the embodied emissions in the cover crop seed (Dewayne, 2013). Cover crops may require an additional operation for termination which may include mechanical treatment such as crimping. We assumed that the energy required for these operations were included in conventional seedbed preparation.

Economic Analysis

For this study, De Laporte et al. (2021) analyzed studies from across the United States and Canada to estimate tillage, seed, planting and kill costs, along with nitrogen savings, compaction, weed control and erosion repair benefits. The estimated net return of rye cover crop ranges from -$314.46/ha to $44.33/ha (Mean=-$85.91/ha). The net return of oat cover crop ranges from -$265.66/ha to $34.00/ha (Mean=-$77.76/ha). The net return of red clover crop ranges from -$107.05/ha to $255.04/ha (Mean=$66.23/ha). The net return of a multi-species mix cover crop with ~70% legumes ranges from -$202.76/ha to $142.05/ha (Mean=-$44.68/ha). The net return of a multi-species mix cover crop with ~50% legumes ranges from -$123.19/ha to $159.63/ha (Mean=$7.77/ha). Net returns benefit here from leguminous crops was due to the nitrogen credit. Large ranges reflect uncertain seeding rates, seed prices, nitrogen credits and weed control benefits that evolve over time. These results indicate that even with cost share program to support cover crops, only a fraction of the potential arable area will be economically attractive for cover crops.

We assume that the above range of economic benefits reflects different inherent biophysical suitability for cover crops and the differing amounts of agronomic benefits from cover crop production. We further assume that the inherent suitability is at least partially represented by the potential rates of adoption by zone and previous cash crop. The differing benefits from cover crop production are related to biomass production by the cover crops, that in our analysis, is proportional to estimated SOC sequestration (i.e., estimated biomass is 4.34 Mg biomass C ha^{-1} * SOC sequestration rate Mg ha^{-1} yr^{-1}/0.32 Mg ha^{-1} yr^{-1}).

Adoption Rate Scenarios

We developed adoption scenarios based on 1) the cost of growing cover crops, 2) the increased N supply from cover crops due to their recovery of leachable N and legume N fixation, 3) the long-term benefits perceived by farmer for the amount of cover crop biomass production, and 4) an external per area payment to induce adoption. For simplicity, we assumed a cover crop mix with 50% legumes. The estimated seeding and terminating for this mix, including machinery costs, was \$115 ha^{-1} (Drever et al. 2021 (accepted)). The N supply benefits can be calculated from table 2.4 and 2.6. We valued N at \$1.2 kg^{-1}. The long-term non-N benefit was assumed to be the long-term average of sum of the effects of cover crop on improving soil health and functioning, on growth promotion of cash crops, on suppressing and controlling pests and diseases in cash crops, and on reducing weed problems. There is definitely no consensus on what equivalent monetary value to place on the above benefits. Lacking better information, we assumed each of the benefits is driven by the amount of cover crop biomass produced. Therefore, the total benefits from cover crop would grow linearly at with cover crop production at a rate that would have an equivalent long-term monetary value. Based on our analysis, the biomass production by the cover crops is proportional to estimated SOC sequestration:

$$AGB = CCseq/0.32 * 3.5$$

where AGB is the estimated above-ground biomass (Mg ha^{-1}) of the cove crop, CCseq is the cover crop C sequestration (Mg C ha^{-1}) from Table 2.2, and 0.32 is the CCseq for 3.5 Mg ha^{-1} of AGB.

We assumed a rate of monetary value increase for cover crop AGB. We also assumed that the increase in the value of the benefits would be greatest for the first units of cover crop production. Therefore, after 1.1 Mg ha^{-1} of estimated of cover crop AGB, we assumed that the rate of accumulation of monetary benefits of cover crop AGB was halved. The estimated cover crop biomass production across Canada ranges from 0.3 to about 3.5 Mg ha^{-1}. For an equivalent value rate of \$10 Mg^{-1} of dry biomass, then, the corresponding total value for cover crop benefits range from \$3 to \$23 ha^{-1}. Obviously, this analysis is simplistic and not based on solid data but provides a way to place a value to non-N benefits from cover crop use that reflects the amount of cover crop growth.

An external per area payment is included that is paid to the farmer to support adoption. Essentially the area payment is a cost share with the grower for the costs of cover crop production. For any cash crop-climate combination where the sum of the value of N, the cover crop non-N benefits from its production, and external area payment exceeded the cost for growing the cover crop, cover crops were assumed to be adopted on that land. The maximum potential rate of adoption (Table 2.1) constrained the land area in cover crops for scenarios that included both relatively high external area payments and value of cover crop production.

The scenarios included external area payments of \$10, 30, 50, and 70 $ha^{-1}$for values of cover crop production of \$5, 10, 20, and 30 Mg^{-1} (Tables 2.7 to 2.10, respectively).

The basic story from the scenarios is that, regarding cover crops, there are two distinct regions: the favoured region for cover crops of the mixed wood plains, Atlantic Maritime and Pacific Maritime and the rest of Canada. The rest of Canada is also complex with a wide variation in attractiveness for cover crops.

For combinations of low external payments and low cover crop value ($5 value with $10 and 30 ha^{-1} external payments and $10 value with $10 ha^{-1} external payment), there was an estimated loss of estimated existing cover crop area in the baseline so there was a net increase in GHG emissions relative to that baseline. Only BC gained a small area of cover crops under these scenarios in the lower mainland and the islands. This analysis also showed movement of land to the most favourable cash crop-climate combinations so that total area under cover crop could drop but the emission reduction from cover crops could increase.

The results indicated in the absence of high external payments, farmers appeared to be valuing the benefits of cover crops equivalent to between $10 and $20 per Mg according to our approach. In fact, with no external per area payment, the same total area of baseline adoption in Canada was estimated to occur with a cover crop value of $17 per Mg (analysis not shown).

In the favoured region, at least 70% of highest adoption occurred for external payments of $70 ha^{-1} regardless of perceived cover crop value or for cover crop value of $30 Mg^{-1} regardless of size of the external payment. Therefore, in this region, incentivizing increased adoption should be possible with sufficient external payments and maintaining that adoption would not require cost-share indefinitely providing farmers to perceive sufficient non-N benefits from cover crops.

In the rest of Canada outside of the favoured region, adoption will be more complex. However, using cover crops on existing fallow in the rest of Canada is particularly attractive, roughly equivalent to the situation in the favoured region. Within this generally less attractive region, the first adoption of cover crop with cash crops occurs in wettest area where the recovery of leachable N adds to the value of cover crops. This is shown by start of adoption (0.28 Mha) of cover crops in Manitoba at the $10 ha^{-1} area payment and $30 Mg^{-1} cover crop value while there is no new adoption of cover crops with cash crops in Saskatchewan or Alberta in that same scenario. This is explained by the combination of wetter climate and higher N fertilizer rates in Manitoba compared with the other prairie provinces that causes more recovery of leachable N by cover crops in Manitoba. As the payment per area rises, more land in the rest of Canada becomes attractive for cover crop adoption. However, appreciable adoption in the dry Canada region only occurs for the scenario of $70 ha^{-1} payment and perceived cover crop value of $30 Mg^{-1}. Adoption in the least favoured parts of the rest of Canada does not provide large GHG emission reductions. For $30 Mg^{-1} cover crop value, more than doubling the area payment from $30 to 70 ha^{-1} increases the total area of cover crop adoption by 6.8 Mha (63%) but only increases the emission reductions by 1769 Mt CO_2e (26%).

The assumed non-N value of cover crop benefits per unit of biomass used in this analysis is less than the general value of hay. Cover crops grown with cover crops would provide graze during fall and/or early spring when many perennial pastures do not provide good grazing and/or are better left ungrazed for the long-term health of the perennial vegetation. Therefore, the value of grazing cover crops may be more than the assumed non-N benefits of cover crops for cash crops. This may be particularly important in the rest of Canada outside of the favoured region for cover crops.

For the favoured region, the results support the analysis of Laporte et al. (2021) that, including the value of benefits from cover crops makes cover crops profitable for adoption on some of the land currently. In the rest of Canada, the results of this analysis show that cases that the area where cover crops adoption is considered profitable without substantial support is limited to either existing fallow or where a farmer perceives an especially large non-N benefit from cover crops. Generally, the net returns without an external per area payment in the rest of Canada are very negative without including potential benefits from grazing cover crops.

Table 2.7: Effect of area payment scenario on added area of cover crops on existing fallow (A/f), added area of cover crops with cash crops (A/c), and emission change (Mit.) from the estimated baseline scenario for a value of cover crop biomass of \$5 Mg^{-1} (negative values are decreases, positive values are increases).

	Area payment with cover crop benefits in excess of N supply valued at \$5 per Mg of cover crop above-ground biomass											
	\$10 ha^{1}			\$30 ha^{1}			\$50 ha^{-1}			\$70 ha^{-1}		
	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.
Province	('000 ha)		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha)		(Gg CO$_2$e yr^{-1})
AB	0	-32	14	1	-32	12	38	-32	-52	92	-32	-114
BC	1	8	-18	2	13	-28	3	17	-35	5	18	-39
MB	0	-13	6	14	-13	-19	32	-13	-48	40	-13	-58
NB	0	-2	2	0	-2	2	0	-1	1	0	22	-24
NL	0	0	0	0	0	0	0	0	0	0	0	0
NS	0	0	1	0	1	-1	0	5	-6	0	15	-15
ON	3	-418	375	4	-418	375	4	-103	-7	4	1244	-1142
PE	0	-4	4	0	-4	4	0	-4	4	0	40	-42
QC	1	-123	103	1	-123	103	1	-74	46	1	502	-440
SK	-7	-59	24	-7	-59	24	107	-59	-175	153	-59	-234
Canada	-2	-643	510	15	-637	472	186	-265	-272	297	1735	-2108

Table 2.8: Effect of area payment scenario on added area of cover crops on existing fallow (A/f), added area of cover crops with cash crops (A/c), and emission change (Mit.) from the estimated baseline scenario for a value of cover crop biomass of \$10 Mg^{-1} (negative values are decreases, positive values are increases).

	Area payment with cover crop benefits in excess of N supply valued at \$10 per Mg ha^{-1} of cover crop above-ground biomass											
	\$10 ha^{1}			\$30 ha^{1}			\$50 ha^{-1}			\$70 ha^{-1}		
	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.
Province	('000 ha)		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha)		(Gg CO$_2$e yr^{-1})
AB	38	-32	-52	45	-32	-62	92	-32	-114	256	361	-480
BC	2	13	-29	3	17	-36	5	18	-39	5	29	-46
MB	28	-13	-43	38	-13	-55	40	-13	-58	40	373	-270
NB	0	-2	2	0	-1	1	0	17	-19	0	30	-30
NL	0	0	0	0	0	0	0	0	0	0	0	0
NS	0	1	-1	0	5	-6	0	15	-15	0	16	-15
ON	4	-418	374	4	-53	-67	4	856	-843	4	1467	-1305
PE	0	-4	4	0	-4	4	0	27	-30	0	58	-55
QC	1	-123	102	1	-74	45	1	436	-390	1	577	-491
SK	107	-59	-174	135	-59	-214	153	-59	-234	564	270	-805
Canada	181	-636	183	227	-215	-389	297	1262	-1743	871	3180	-3497

Table 2.9: Effect of area payment scenario on added area of cover crops on existing fallow (A/f), added area of cover crops with cash crops (A/c), and emission change (Mit.) from the estimated baseline scenario for a value of cover crop biomass of \$20 Mg^{-1} (negative values are decreases, positive values are increases).

	Area payment with cover crop benefits in excess of N supply valued at \$20 per Mg ha^{-1} of cover crop above-ground biomass											
	\$10 ha^{1}			\$30 ha^{1}			\$50 ha^{-1}			\$70 ha^{-1}		
	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.
Province	('000 ha)		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha)		(Gg CO$_2$e yr^{-1})
AB	92	-32	-114	256	-32	-270	256	2360	-1361	256	3173	-1637
BC	5	18	-39	5	18	-39	5	47	-54	5	65	-60
MB	40	-13	-58	40	-13	-58	40	2451	-1142	40	2795	-1262
NB	0	15	-18	0	25	-27	0	34	-32	0	34	-32
NL	0	0	0	0	0	0	0	0	0	0	0	0
NS	0	11	-12	0	16	-15	0	16	-15	0	16	-15
ON	4	304	-383	4	1463	-1302	4	1483	-1313	4	1498	-1319
PE	0	23	-27	0	52	-52	0	67	-60	0	67	-60
QC	1	248	-245	1	536	-467	1	611	-506	1	620	-510
SK	154	-59	-235	564	-59	-629	564	2523	-1801	564	4696	-2600
Canada	297	515	-1131	871	2005	-2860	871	9590	-6284	871	12964	-7495

Table 2.10: Effect of area payment scenario on added area of cover crops on existing fallow (A/f), added area of cover crops with cash crops (A/c), and emission change (Mit.) from the estimated baseline scenario for a value of cover crop biomass of \$30 Mg^{-1} (negative values are decreases, positive values are increases).

	Area payment with cover crop benefits in excess of N supply valued at \$30 per Mg ha^{-1} of cover crop above-ground biomass											
	\$10 ha^{1}			\$30 ha^{1}			\$50 ha^{-1}			\$70 ha^{-1}		
	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.	A/f	A/c	Mit.
Province	('000 ha)		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha		(Gg CO$_2$e yr^{-1})	('000 ha)		(Gg CO$_2$e yr^{-1})
AB	256	-13	-281	256	2494	-1417	256	3118	-1622	256	4910	-2052
BC	5	24	-43	5	49	-55	5	60	-59	5	116	-73
MB	40	279	-219	40	2504	-1163	40	2784	-1259	40	2853	-1274
NB	0	29	-29	0	34	-32	0	34	-32	0	34	-32
NL	0	0	0	0	0	0	0	0	0	0	0	0
NS	0	16	-15	0	16	-15	0	16	-15	0	16	-15
ON	4	1466	-1304	4	1494	-1317	4	1498	-1319	4	1498	-1319
PE	0	55	-54	0	67	-60	0	67	-60	0	67	-60
QC	1	562	-482	1	617	-509	1	620	-510	1	620	-510
SK	564	-56	-631	564	3697	-2279	564	4683	-2596	564	7668	-3282
Canada	871	2362	-3059	871	10972	-6847	871	12880	-7471	871	17782	-8616

Policies Required to Increase Cover Crop Adoption

Growing cover crops are a complicating activity that needs to mesh well with all the existing activities of cash crop production. Expanding cover crop adoption throughout Canada with appropriate programming will provide the essential practical farm experience on the challenges and benefits of cover crops to share within the farm community. Gaining more experience immediately is necessary to discern best practices to have substantial cover crop adoption by 2030. We considered that an immediate goal would be to increase cover crop area on the prairies by 1% of cropland area to obtain more farmer experience with cover crops in that region where cover crops are currently an unusual practice. Outside of the prairies, cover crops already have a foothold so the goal is to increase adoption by about 15% of cropland area to broaden experience and ultimately acceptance of cover crops as a beneficial practice. Given the limited information on the exact long-term benefits of cover crops, to attract farmers to adopt cover crops will require conservative estimates of the non-N benefit for cover crops. We assumed farmers outside of the Prairies may value the non-N benefits of cover crops at $8 per tonne of cover crop biomass. However, for the prairies we set that rate for non-N benefits at $5 per tonne. The results show that it would be possible to achieve 2.1 Mt of CO_2e reduction for a cost of about $115M for area payments (Table 2.11).

Table 2.11: Cover-crop payments required to rapid expansion of cover crop by 1% of cropland area on the prairies and 15% of cropland area outside the Prairies.

Part of Canada	Area Payment ($/ha)	Non-N cover-crop value ($/t above-ground biomass)	Total area of cover crops ('000 ha)	New cover-crop area (% of cropland)	GHG emission reductions (Gg/yr)	Total Area Payments ($M/yr)
Prairies	77.90	$5	460	1.0	621	35.8
Rest of Canada	53.95	$8	1463	15.4	1437	78.9
All of Canada	--	--	1923	5.0	2058	114.7

Based on our analyses, encouraging cover crop adoption will need supports that vary regionally across Canada. In favoured region (Mixed Wood Plains and Atlantic and Pacific Maritime climates), cost share for cover crop establishment should be effective to increase adoption since there are already substantial estimated N and non-N benefits from cover crop. As the benefits of cover crops grow to exceed the costs, the amount of cost share can be decreased and eventually dropped as the economic benefits of cover crops exceed the costs, at least for the most favourable combinations of cash crops and cover crops.

In the rest of Canada outside the favoured region, our analysis shows it will take additional support to significantly grow cover crop adoption initially. Since the amount of biomass production will always be limited in that climate, there needs to be research and development on cover crop species and species mixes that provide the significant agronomic benefit in those soils and climates even with relatively low amounts of cover crop growth. There is also a need to research cover crop cultivars and techniques that can establish well in an interseeded situation into conventional solid seeded (i.e., non-row crops) cash crops to maximise growth potential in the fall. There is also need research and development for cover crop cultivars that overwinter well and/or can be seeded into cold soil for successful germination and establishment the next spring. Such cultivars would maximize the opportunity to use early spring growing period for cover crops before the next cash crop. In this region, there is often problems with excessive wetness in the spring and cover crops growing during that early spring period could even allow earlier seeding of cash crops on some fields. Research and development of cover crop production systems that provide good benefits with cattle grazing of the cover crops is also important in this region. With cover crop technologies applied to favourable situations, there should be cover crop adoption without ongoing public support.

In the semiarid parts of the rest of Canada, the climate restrictions for cover crops are severe. Although there may be sufficient warmth for cover crop growth in fall or early spring, water availability will often limit growth and may even prevent successful cover crop establishment at all. Although the best growing period for cover crops in this region may be the early spring, growing cover crops then could dry out the soil sufficiently that it substantially reduces yield of the subsequent cash crop. Therefore, the potential benefits are small, and could be negative since they reduce water conservation, so that it will require at least full cost coverage initially to incent any meaningful adoption. The research and development efforts outlined for rest of Canada to maximize the benefits of cover crops for low biomass production would be particularly important in semiarid Canada. The grazing value of cover crops in this area may be particularly important since cover crops can provide better grazing in the fall than existing perennial pastures. However, realistically, cover crop adoption will always be more opportunistic when particularly favourable circumstances, including capacity to incorporate cattle grazing, align that make cover crops attractive than becoming a routine practice in the semiarid region.

The applied research into cover crop systems to support the adoption of best practices is needed but must be relevant to actual farm situations. Conducting much of this applied research to improve cover crop systems on model farms, then, would be most effective.

Co-benefits

Positive

With the possible exception of increased N_2O emissions, in a meta-analysis, Daryanto et al. (2018) found that, overall, the ecosystem services from cover crops are positive and they should be a recommended practice for all cropland. Cover crops reduce dust from wind erosion (Baumhardt et al., 2015), increase biodiversity of soil organisms (Elhakeem et al., 2019) and increase animal population by providing browse, nectar, and/or cover. They also reduce soil erosion and increase soil health including organic carbon (Daryanto et al., 2018). Cover crops reduce nitrate leaching (Thapa et al. 2018) and can reduce nutrient loss in runoff (Dabney et al., 2001). There are increased economic opportunities in rural areas for growing and processing cover crop seed and for potential contracted services of planting and/or terminating cover crops.

Negative

There is concern about cover crop increasing P losses in winter and spring runoff (Daryanto et al., 2018), an important potential P-loss pathway for Canada (Liu et al., 2019). However, field studies with cover crops in Canada, while limited, have not shown an increase in P loss (Lozier et al., 2017; Schneider et al., 2019). Further investigation is needed to determine if cover crop adoption may need some restrictions because of potential P losses to surface water (Liu et al., 2019).

Limitations and Additional Opportunities beyond Scope

While this analysis is thorough, it remains limited because of a lack of research in the Canadian.

- More research is needed about the GHG mitigation effects of cover crops across Canadian conditions, including cover crop effects on both SOC change and on N_2O emissions. For N_2O emissions, it is important that the emissions are quantified during growth of the cover crop until at least harvest of the subsequent cash crop so that the full effect of the cover crop is determined. The effect of cover crop on N balance and on the response to N of subsequent cash crops requires more research in Canadian conditions.

- The various agronomic benefits of cover crops, directly from the cover crops themselves (e.g., N fixation by legumes), and their effect on soil health needs to be better quantified to inform decision-makers about merits of cover crop adoption.

- The effect of cover crops on P loss to surface water requires more research to determine if there needs to be restrictions on cover crop adoption in some watersheds in Canada.

- There is also a need for research and development on cover crop species, mixes, and cultivars that are provide maximum agronomic and soil benefits under conditions of low potential biomass production is important, particularly outside of warm and moist Canada.

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3. The environmental benefits of Rotational Grazing in Canada

Introduction

In Canada, grazing land covers 18.7 million hectares, about 1/3 of the total land area used for agriculture in Canada. Grazing land consists of natural land used for grazing and tame pasture. The former is normally permanent with low level of external inputs and consists of native species, a mix of native and tame species (possibly seeded tame or invasive tame), or primarily tame species (the latter sometimes called naturalized grassland (Sheppard et al., 2015)). In contrast, tame pastures are typically terminated and reseeded periodically when productivity declines and/or when there is a presence of excessive undesired plant species. In 2006, 32% of tame pasture managers rejuvenated tame pasture every 5 years or less, and 40% every 6-10 years, with 11% never being rejuvenated (Sheppard et al., 2015). In 2011, 13% of tame pastures received fertilizer (Sheppard et al., 2015) and, on average, 22% of the vegetation sward was legume (Sheppard et al., 2015) – two practices that increase productivity and forage quality.

Rotational grazing is the practice of moving grazing cattle through a set of paddocks. It is in contrast to continuous grazing where cattle are in a single paddock through the grazing season. The main advantages of rotational grazing is increased vegetation growth (Alemu et al., 2019; Sanderman et al., 2015) and better graze quality (Wang et al., 2015), although this is not necessarily universal as Popp et al. (1997) found no significant effect on either herbage quantity or quality from rotational grazing in Manitoba. There is a wide range of grazing practices within rotational grazing. Basic rotational grazing provides the opportunity for grazed plants to recover. Intensive rotational grazing has much shorter duration of grazing, moving animals more often, so as to reduce stress on the plant from grazing (sometimes referred to as avoiding the "second bite" of any plant during a grazing period) and allowing for sufficient time for plant recovery after grazing. Unfortunately, there are not widely accepted definitions of the range of practices.

For this analysis we divided rotational grazing into 5 classes:

1) Continuous: no rotational grazing, continuous season-long grazing
2) Basic, simple: rotational grazing in which animals are rotated through multiple paddocks once.
3) Basic, advanced: multiple paddocks, in which animals are rotated through each paddock at least once and/or grazing is deferred in each paddock over years for critical vegetation growth periods to maintain good pasture condition.
4) Intensive, simple: 7 or more paddocks, with short grazing duration (< 10 days) per paddock with duration between grazing on each paddock based on sufficient time to reach desired vegetation state for long-term vegetation health.

5) Intensive, advanced: multiple paddocks grazed for 1 day or less per paddock, with duration between grazing on each paddock based on sufficient time to reach desired vegetation state for long-term vegetation health.

Rotational grazing is applicable for all grazing animals including sheep, goats, horses, and cattle. This report will look at rotation grazing specifically for beef cattle because this is the largest livestock group for pasture management in Canada.

Currently, about 50% of beef producers use rotational grazing according to 2016 Census of agriculture (Beef Cattle Research Council, 2019) with a percentage adoption similar across provinces. In 2011, about 25% of beef producers reported using continuous grazing on tame pasture and 35% using continuous grazing on native pastures (Sheppard et al., 2015). Fully 66% of beef producers had 2-4 paddocks for tame pasture and 58% had 2-4 paddocks for native pastures in 2011 (Sheppard et al., 2015). These would be classed as basic rotational grazing by our definition. In 2014, 10.8% and 7.8% of cow-calf producers in western Canada used intensive rotational grazing management on owned tame pasture and native range, respectively. In northern Ontario and Quebec in 2015, about 30% used continuous grazing, 50% basic rotational grazing and about 20% use intensive rotational grazing (Beef Cattle Research Council, 2019). The lack of standard definitions makes it difficult to interpret and reconcile surveys. Because of characteristics of different pasture areas and the different feed requirements of different groups of livestock, a producer could have some pasture area with continuous grazing, some with basic rotational grazing, and/or some with intensive rotational grazing; this adds to confusion when survey asks for only one type of grazing system.

Kristine et al. (2021) surveyed grazing practices for 97 pastures on 28 ranches distributed across southern and central Alberta to assess the effect of grazing and other factors on range health. The ranchers were volunteers so may have been more inclined to be interested in range health and thereby possibly more likely to use rotational grazing. Nevertheless, only two pastures, both tame, had a grazing period of 1 day and so correspond to advanced intensive grazing. Nineteen pastures (included 5 native pastures) had grazing period of 2-9 days so would be simple intensive rotational grazing in our nomenclature. Thirteen pastures (7 native and 6 tame) had a grazing period over 60 days indicating continuous or a rudimentary basic rotation grazing. Twenty-two pastures had a grazing period of 10-21 days which would fit best the definition of advanced basic rotational grazing in our system. The remaining 42 pastures with grazing period between 22-60 days would be basic rotational grazing. Of note, range health scores, for both native and tame pastures, tended to decrease linearly as grazing period lengthened. This is consistent with the concept that moving to more intensive rotational grazing improves the quality of pasture which improves soil quality.

The general trend in Canada is towards increased rotational grazing and a shift towards intensive rotational where pasture area is suitable (water sources and topography). Rotational grazing is promoted by the Canadian beef industry and governments.

Methods for Estimating Greenhouse Gas Emissions and Carbon Sequestration

Background Greenhouse Gas Fluxes

The grasslands of Canada are gaining an average of 130 kg C ha^{-1} yr^{-1} during the early 2000s based on atmospheric inversion models (USGCRP, 2018), although this value refers primarily arctic tundra grasslands in additions grazing land. In the Great Plains, grasslands in the same period were a sink of 240 kg C ha^{-1} yr^{-1} and are expected to remain a sink at a similar rate to 2050 (USGCRP, 2018). Nevertheless, the rate varies widely by year, including being a source in drought years, in response to weather. Grazing generally increases SOC compared to no grazing (McSherry and Ritchie, 2013) with rates of 72 to 190 kg C ha^{-1} yr^{-1} in the northern Great Plains (Wang et al., 2016; Wang et al., 2014). Smith (2014) cautions that grasslands cannot be expected to be a perpetual sink as they will come to an equilibrium C after which there will not be sustained increases in C stocks. Therefore, much of observed increases may be due to recent improved grassland management that is restoring SOC that was lost from past poor management. In agreement with this, Wang et al. (2014) relates the increase in SOC on rangelands from simply grazing in the Northern Great Plains to likely restoration of SOC after mismanagement, particularly over stocking, in the first half of the 20th century. Similarly, initial findings showed that European grasslands appeared to be a continual sink of C as high as 1.29 Mg C ha^{-1} yr^{-1}, sufficient to more than offset the emissions of CH_4 and N_2O from the grazing livestock (Soussana et al., 2010). However, Chang et al. (2016) showed that this SOC increase is the result of significant lowering of stocking on European grasslands due to policy changes during the 1980s and 1990s. Therefore, the European grassland sink will decrease over time as it approaches a new SOC equilibrium. For this study, we did not assume C sequestration rates for rotation grazing required SOC recovery from a historically more soil-degraded condition of the grazing lands, but a number of the studies used to estimate rotational grazing effects may include the contribution from such SOC recovery.

Soil Organic Carbon Change from Adoption of Rotational Grazing

New adoption of rotational grazing represents an opportunity to increase SOC on pastures. The available data (Table 3.1) does not allow robust analysis of additional C sequestration from adoption of rotational grazing in Canada since there are few studies for Canada and results are variable elsewhere. The general results globally are that rotational grazing increases SOC (Byrnes et al., 2018). The majority of the effects on SOC were either zero or positive, consistent with assumption that benefits are generally positive.

Byrnes et al. (2018) found that rotational grazing had greatest positive effects in humid climates. Compared with continuous grazing, grazing exclusion tends to increase SOC in wetter climates and decrease SOC in drier climates with the effect being linear with precipitation in the range of 200 to 1000 mm (Derner and Schuman, 2007; Hu et al., 2016; McSherry and Ritchie, 2013). This also supports the concept that rotational grazing will be more effective for increasing SOC as precipitation increases as the long vegetation recovery time without grazing inherent to rotational grazing mimics some aspects of no grazing.

Having legumes in pasture has been shown to improve C sequestration (Conant et al., 2017; Fornara and Tilman, 2008; Henderson et al., 2015) and improve herbage quality (Bélanger et al., 2017; Peprah et al., 2018). The recovery periods and reduced sustained grazing stress with rotational grazing improves longevity and maintenance of seeded legumes (Forsythe, 2018). We assumed that all natural and tame pasture under intensive grazing will also be managed so that they will have sufficient legumes to provide N needs of the sward whereas the continuous and basic scenarios may or may not have adequate legume content.

Table 3.1: Values of SOC sequestration for rotational grazing

Location	Duration (yr)	Study type	Comparison	C sequestration rate (kg C ha^{-1} yr^{-1})	Reference	Comments
Global	1-98	Meta-analysis of published results	Rotational vs continuous	Can't be calculated from data provided	(Byrnes et al., 2018)	Rotation 32% higher (ln RR = 0.28)
Temperate and tropical	N/A	Modelling study but model only validated for ranches in Montana	Multi-paddock vs continuous	Temperate: 16-pasture vs 4 pasture: 0-60 4 pasture vs continuous: 0-1000+ (rates assuming 80 years to equilibrium (Derner and Schuman, 2007)	(Ritchie, 2020)	Continuous grazing was estimated to be losing SOC comparison versus continuous depends hugely on stocking rate
US grazing lands	N/A	Expert opinion		Rangeland: 50 to 150 Tame Pasture: 300-1300	(Follett et al., 2001)	
New York, USA	N/A	Modelling (Comet-VR)	Cropland to rotational grazing	3510	(Rosenzweig et al., 2010)	
Virginia, USA	20		Change to rotational grazing on existing pasture	790	(Bosch et al., 2008)	
Saskatchewan	N/A	Modelling	Change to rotational (basic) grazing on tame pasture in Black soil zone	65	(Lynch et al., 2005)	
Saskatchewan	18	measurement	Rotational (advanced basic) grazing compared to continuous native species mix established on cropland	200 (0-60 cm)	Iwaasa (unpublished), experiment described in (Alemu et al., 2019)	P=0.09
US grazing lands	N/A	Expert opinion		Rangeland: 70 to 300 Tame pasture: 300 to 1400	(Morgan et al., 2010)	
Manitoba	5	Measurement	Rotational grazing (intensive) on tame pasture vs continuous	340	(Manas et al., 2000)	Results not statistically signficant
Michigan	4	Measurement	Rotational (intensive) grazing (change over time, no	3540	(Stanley et al., 2018)	Authors caution that rate may not continue for

Location	Duration (yr)	Study type	Comparison	C sequestration rate (kg C ha^{-1} yr^{-1})	Reference	Comments
			comparison)			long duration
SE US	7	Measurement across farms, comparison with row crop agriculture	Change from intensive grazing on pasture established on long-term cropland	8000	(Machmuller et al., 2015)	Dr. A. Franzleubers, in written comments to journal, points out flaws in study and suggests that rate of 1590 kg C/ha/yr is more plausible from the data
Alberta	30	Modelling with validated Century model across Alberta	Change to rotational grazing for rangeland	Rotational grazing with long duration grazing: -400 to -100 (loss) Rotational grazing with short duration grazing duration: 100-200 kg C/ha/yr 10% reduction in stocking rate 200-300 across all grazing practices	(Iravani et al., 2020)	
Global	N/A	Review of published results	“improved grazing” assumed to rotational grazing	280	(Conant et al., 2017)	
South Dakota	30+	Measurement across ranches	Rotational grazing vs continuous	0	(Hillenbrand et al., 2019)	
Prairies	?	Measurement across ranches	Adaptive multi-paddock vs conventional practices	0	(Breitkreuz et al., 2019)	No evidence of difference
Global		Review of published literature	Rotational (Hollistic) grazing vs continuous	0	(Hawkins, 2017)	No evidence of difference from available studies
Australia	5-15	Measurement across adjacent farm paddocks		0	(Sanderman et al., 2015)	
Belgium		CO2 flux by eddy covariance, 1 pasture each	Rotational vs continuous	0	(Gourlez de la Motte et al., 2018)	

Location	Duration (yr)	Study type	Comparison	C sequestration rate (kg C ha^{-1} yr^{-1})	Reference	Comments
		system				
Texas (tallgrass prairie)	15 yr	CO2, N2O, and CH4 fluxes for 2 yeaers on neighbouring ranches	Continuous vs Adaptive multi-paddock grazing (AMP=rotational grazing)	CO2 emissions smaller proportion of plant production for AMP vs continuous, AMP N2O fluxes about ½ of continuous	(Dowhower et al., 2020)	Not possible to derive a SOC sequestration rate
Texas (tallgrass prairie)	9+	Soil sampling on neighbouring ranches	Continuous vs AMP	1300 (continuous heavy vs AMP heavy stocking rate) 130 continuous light stocking vs AMP heavy stocking rate)	(Teague et al., 2011)	Data does not allow for precise derivation of rate, value based on 15 years in practice.
Wyoming	11	Experiment on native rangeland	Continuous heavy vs deferred heavy and short duration heavy	0 for continuous heavy vs. short duration, -590 (loss) for continuous heavy vs deferred heavy grazing	(Manley et al., 1995)	all treatments with stocking for heavy grazing had less SOC than continuous light grazing
Alberta	5	Native rangeland	Deferred rotational vs non grazing	0 difference between treatments	(Dormaar et al., 1997)	Grazing pressure was very light
The Netherlands	5	Tame pasture	Continuous vs rotational experiment	-300 (loss) for rotational for 0-30 cm, 0 for 0-60 cm	(Hoogsteen et al., 2020)	Grazing was simulated with vegetation harvest
Switzerland	1	Tame pasture	Flux measurement of rotation grazing only	With rotational grazing and considering CO2, CH4, and N2O, the system was net reduction of global warming potential (net sink in terms of soil C	(Voglmeier et al., 2020)	No comparison with alternate grazing systems
Canadian Prairies	10+	Ranch grasslands	Adaptive multi-paddock grazing vs non-AMP between ranches	Soil under AMP has increased CH4 uptake and not increase in CO2 of N2O emission	(Shrestha et al., 2020)	Lab incubation study so can not be extrapolated to actual rates in the

Location	Duration (yr)	Study type	Comparison	C sequestration rate (kg C ha^{-1} yr^{-1})	Reference	Comments
						field
Argentina	8	Ranch, saline soils	Rotational vs continuous	560 for rotational vs continuous	(Vecchio et al., 2018)	Difficult to estimate precisely from data provided

From the available data (Table 3.1) and our expert opinion, we estimated a conservative average C sequestration rates that would be applicable over 30 years (Table 3.2). For this purpose, we divided Canada into 3 general climatic zones: moist and warm Canada (Mixed Wood Plains, Pacific Maritime, and Atlantic Maritime Ecozones), dry Canada (Brown and Dark Brown soil zones of the Prairie Ecozone), and moist and cool Canada (Montane Cordillera, Boreal Plains, Black, Dark Gray, and Gray soil zones within the Prairie, and Boreal Shield Ecozones). We expect there will be a wide range of values on a paddock-by-paddock and year-by-year basis depending on the initial state of soil degradation when rotational grazing is adopted, the weather patterns, and, especially for natural pasture, the initial species mix. Note that rates of 100 kg C ha^{-1} yr^{-1} or less would be difficult to detect through measurement and so may be reported in scientific literature as no change. The values are highly uncertain due to limited amount of evidence specific to Canada. Therefore, we suggest that uncertainties would be in the order of ±100%, i.e., ranging from no change to double the derived gains.

Table 3.2: Estimated mean rates of C sequestration from changing from continuous grazing for different levels of rotational grazing and pasture area for climatic zone in Canada when.

Pasture Type	Grazing	Zone Moist and warm Canada*	Dry Canada*	Moist and cool Canada*
Natural land	Area (M ha) =	1.338	7.120	5.277
	Grazing method	--- C sequestration from continuous (kg C ha^{-1} yr^{-1})----		
	Simple Basic	60	20	40
	Advanced Basic	80	30	60
	Simple Intensive	200	60	120
	Advanced Intensive**	200	60	120
Tame	Area (M ha) =	0.285	1.753	2.949
	Grazing Method	--- C sequestration from continuous (kg C ha^{-1} yr^{-1})----		
	Simple Basic	80	30	60
	Advanced Basic	200	60	120
	Simple Intensive	400	120	240
	Advanced Intensive**	400	120	240

* Moist and warm is 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.

**there was insufficient data to distinguish between simple and advanced intensive, anecdotal evidence indicate there could be substantial SOC increases from adoption of advanced intensive.

Enteric Fermentation

We used the HOLOS model[6] to estimate the potential effect of rotational grazing on other emissions and ran a simulation with 1000 cows and 850 calves. The emissions for 150-day grazing season are shown in Table 3.3. The enteric fermentation emissions were reduced due to improved feed quality in summer and early fall for rotational grazing and reduced walking during grazing for cattle in intensive rotational grazing. These emission reductions can be as important as soil C sequestration. These non-SOC emission reductions are highly uncertain because they depend on assumptions of increased forage quality with rotational grazing. Some studies show increased forage quality with rotational grazing (Billman et al., 2020), others show no effect (Popp et al., 1997), while others show a reduction

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[6] https://www.agr.gc.ca/eng/scientific-collaboration-and-research-in-agriculture/agricultural-research-results/holos-software-program/?id=1349181297838

(Alemu et al., 2019). In their meta-analysis (McDonald et al., 2019) found that a long rest period, essential to advanced (basic and intensive) rotational grazing increased cattle productivity per ha, generally associated with better forage quality. An exception may be semiarid natural grasslands which show that rotational grazing may produce lower rates of cattle weight gain than continuous grazing (Augustine et al., 2020; Derner et al., 2008) although, Ritchie (2020), using a model validated with measured data for the semiarid northern Great Plains, concluded that rotational grazing would increase cattle productivity per ha over the long term. Given this evidence, we assumed no reduction in enteric fermentation emission for natural pastures in the dry climate zone. However, we assumed that conservative equivalent reduction, expressed in units of C, equal to 1/4 of the C sequestration rates in Table 3.2 can be added to the GHG fluxes, to account for impact on reducing enteric fermentation for all climate and pastures except natural pastures in dry climates.

Table 3.3: Estimated emissions for enteric fermentation and from manure deposited on pasture for 1000 600 kg beef cows with 850 calves during summer grazing season.

	Natural pasture			Tame Pasture		
Grazing Method	Emission (t CO_2e)	Total Paddock Area (ha)	Reduction compared to Continuous (kg CO_2e ha^{-1})	Emission (t CO2e)	Total Paddock Area (ha)	Reduction compared to Continuous (kg CO_2e ha^{-1})
			Dry Canada			
Continuous	3562	4000	0	3483	3200	0
Basic	3310	3900	65	2976	3000	169
Intensive	3054	3800	133	2400	2800	386
			Moist and Cool Canada			
Continuous	3562	2000	0	3215	1600	0
Basic	3248	1900	165	2758	1400	330
Intensive	2481	1800	600	2275	1200	780
			Moist and warm Canada			
Continuous	2988	750	0	2758	600	0
Basic	2523	710	650	2399	525	683
Intensive	2318	675	993	2109	450	1442

Adoption Rate Scenarios

Adoption Potential

The primary barriers to adoption of rotational grazing are cost for necessary watering facilities and fencing, increased labour requirement to carefully monitor pastures and to move cattle between paddocks. A well-designed grazing plan is necessary both to design the infrastructure and to operationalize rotational grazing.

By 2030, we assumed that there is technical potential to have substantial increases in advanced basic and intensive rotational grazing, particularly in the Moist and Warm and Moist and Cool climates. Table 3.4 lists the estimated current and potential 2020 adoption rates. To realize this potential, there needs to be sufficient capacity for grazing practices, either from advisors or from farmer/rancher training, and building confidence that rotational grazing will have economic benefits that are larger than the increased costs. Cost-share for the costs, especially for up-front costs for infrastructure improvements, help build that confidence of positive net economic benefit from rotational grazing. With greater experience and more evidence of positive results gleaned from nearby adopters over time, more farmers should increase confidence of the merits of adoption without necessarily requiring any cost-share. Water availability was assumed to limit the extent of adoption of intensive grazing in dry climates, particularly for natural pastures.

Actual Adoption

The fewest barriers for improving grazing management for continuous and simple basic practices is the adoption of advanced basic because 1) lowest requirement for new water sources and 2) lowest additions for required infrastructure and labour. The barriers to adopting intensive rotational grazing are more formidable from continuous or basic practices since entails larger additions to infrastructure and labour. The adoption of advanced intensive rotational grazing can involve a lifestyle change because of the need for daily cattle movement. Producers are probably more likely to move incrementally than to make large jumps in management, i.e., preferring to transition from continuous to basic, from simple basic to advanced basic, from advanced basic to simple intensive, and from simple intensive to advanced intensive. Consequently, to increase adoption of intensive grazing requires increasing the transition from continuous to simple basic and simple basic to advanced basic. Farmers might not transition all their herd to an improved grazing management so could have a mix of grazing practices during transition. Further, until they gain knowledge and experience in monitoring their pasture states that is essential for advanced basic rotation grazing or simple intensive grazing, they may have the infrastructure for more advanced or intensive rotational grazing but manage it more consistent with simple basic rotational grazing practices.

We considered two additional scenarios for adoption. The first scenario was modest adoption with emphasis on reducing the use of continuous grazing with modest increases in advanced basic and intensive rotational grazing. The second scenario was more ambitious with reduction of continuous and simple basic with associated greater adoption of advanced basis and intensive grazing.

Change in Greenhouse Gas Emissions

We assumed that the current practices have been in place sufficiently long that no additional sequestration is taking place. We also assumed that grazing practice changes are incremental and additive. To illustrate, the C change rate from continuous to intensive rotational for moist and warm climate has a 400 kg C ha^{-1} yr^{-1} and so the C change rate from long-term simple basic is the intensive for tame pasture is 400 kg C ha^{-1} yr^{-1} change from continuous to intensive – 80 kg C ha^{-1} yr^{-1} for continuous to simple basic (the subtraction accounts for the fact that higher SOC for the long-term simple basic rotational grazing adoption). With this assumption the pathway to more advanced and intensive rotational grazing systems do not affect the net result. For example, the carbon gain from converting 1 ha from continuous to intensive grazing is the same GHG emission change as converting 1 ha from continuous to simple (basic) and another ha from simple (basic) to intensive. With this assumption, the exact pathway of advancement and intensification of rotational grazing does not affect net reductions.

The scenario of technical potential adoption and the associated GHG reduction from a baseline of current adoption are shown in Table 3.4. The majority of the total 3.65 Mt CO_2e reduction in 2030 is in Moist and Cool climate, that is primarily the subhumid areas of the Prairies. Although 47% of Canada's grazing lands are in semiarid prairies, this area only contributed 14% of potential emission reductions. The total emission reductions from this zone are relatively small, both because there was assumed to be less shift to more advanced and intensive rotational grazing and the rates of emission reduction are smaller than other zones per hectare.

We investigated three scenarios of adoption: 1) 5% increase in area under advanced basic (2.2% more of grazing land) and intensive (2.8% more of grazing land) under budget 2020, 2) a modest increase to 2030, and 3) an ambitious adoption scenario to 2030. The scenarios and greenhouse emission reductions are presented in Table 3.5, 3.6, and 3.7, respectively. The reductions of 0.405, 1.60 and 2.12 Mt CO_2e for these three scenarios were 11, 44, and 58% of the maximum potential of 3.65 Mt CO_2e in 2030.

Table 3.4: : Scenario of technical potential adoption and its greenhouse gas emission reductions in 2030 by climate zone.

	Climate					
	Moist and Warm		Dry		Moist and Cool	
Grazing System	Current	2030	Current	2030	Current	2030
	------------ Natural Pasture Adoption Rates (% of area) --------------					
Simple basic	50	20	50	50	50	25
Advanced basic	10	20	10	25	10	25
Intensive	10	55	5	15	10	45
	------------ Tame Pasture Adoption Rates (% of area) --------------					
Simple basic	40	20	50	35	40	20
Advanced basic	20	15	10	35	20	20
Intensive	10	60	5	25	10	55
	--- Decrease in Greenhouse Gas Emissions (Mt CO_2e/yr) ---					
All Natural Pasture	--	0.53	--	0.32	--	0.99
All Tame Pasture	--	0.23	--	0.28	--	1.30
Total Pasture	--	0.76	--	0.50	--	2.29

Table 3.5: Scenario of 5% more area with rotational grazing and its greenhouse gas emission reduction by climate zone.

			Climate			
	Moist and Warm		Dry		Moist and Cool	
Grazing System	Current	2030	Current	2030	Current	2030
	------------ Natural Pasture Adoption Rates (% of area) --------------					
Simple basic	50	50	50	50	50	50
Advanced basic	10	12.2	10	12.2	10	12.2
Intensive	10	12.8	5	7.8	10	12.8
	------------ Tame Pasture Adoption Rates (% of area) --------------					
Simple basic	40	40	50	50	40	40
Advanced basic	20	22.2	10	12.2	20	22.2
Intensive	10	12.8	5	7.8	10	12.8
	--- Decrease in Greenhouse Gas Emissions (Mt CO_2e/yr) ---					
All Natural Pasture	--	0.05	--	0.06	--	0.11
All Tame Pasture	--	0.02	--	0.04	--	0.13
Total Pasture	--	0.07	--	0.10	--	0.2

Table 3.6: Scenario of modest adoption of improved grazing (focus n increasing basic rotational grazing) and its greenhouse gas emission reductions in 2030 by climate zone.

			Climate			
	Moist and Warm		Dry		Moist and Cool	
Grazing System	Current	2030	Current	2030	Current	2030
	------------ Natural Pasture Adoption Rates (% of area) --------------					
Simple basic	50	50	50	62	50	50
Advanced basic	10	30	10	15	10	30
Intensive	10	15	5	8	10	15
	------------ Tame Pasture Adoption Rates (% of area) --------------					
Simple basic	40	35	50	60	40	35
Advanced basic	20	40	10	25	20	40
Intensive	10	20	5	10	10	20
	--- Decrease in Greenhouse Gas Emissions (Mt CO_2e/yr) ---					
All Natural Pasture	--	0.16	--	0.15	--	0.44
All Tame Pasture	--	0.10	--	0.15	--	0.61
Total Pasture	--	0.26	--	0.30	--	1.05

Table 3.7: Scenario of ambitious adoption of improved grazing (combined focus on increasing rotation grazing including advanced basic and intensive) and its greenhouse gas emission reductions in 2030 by climate zone.

	Climate					
	Moist and Warm		Dry		Moist and Cool	
Grazing System	Current	2030	Current	2030	Current	2030
	--------------------------- Natural Pasture ---------------------------					
Simple basic	50	40	50	55	50	40
Advanced basic	10	30	10	20	10	30
Intensive	10	25	5	10	10	25
	--------------------------- Tame Pasture ---------------------------					
Simple basic	40	30	50	50	40	30
Advanced basic	20	35	10	30	20	35
Intensive	10	30	5	15	10	30
	--- Decrease in Greenhouse Gas Emissions (Mt CO2e/yr) ---					
All Natural Pasture	--	0.21	--	0.19	--	0.58
All Tame Pasture	--	0.13	--	0.19	--	0.91
Total Pasture	--	0.34	--	0.38	--	1.39

Co-benefits

Positive

Rotational grazing has important co-benefits of maintaining and increasing biodiversity. Rotational grazing improves soil health (Byrnes et al., 2018), increases above and below ground biodiversity (Reshmi et al., 2020; Teague and Kreuter, 2020), and maintains legumes that reduce need for nitrogen fertilizer (Forsythe, 2018). Natural grazing lands are important reservoirs of plant, animal and soil biota biodiversity within the land base and support biodiversity of many animals that use grasslands but also migrate beyond that grazing land base.

Negative

Moving to more advanced and intensive rotational grazing will probably reduce the area of grazing land required as the same amount of cattle can be fed on smaller land area. Other things equal, this leads to a drop in grazing area and incentive to convert grazing land to cropland. This conversion results in loss of biodiversity, loss of soil, nutrients and pesticides to the environment, increased greenhouse gas emissions from nitrogen, and loss of soil organic carbon.

Addressing Negative Co-benefits

The conversion of grazing land to cropland is an important potential issue associated with adoption of more advanced and intensive rotational grazing. Importantly, this may be exacerbated by the decline in the Canadian beef cattle herd. The beef cattle herd has been dropping steadily for many years. In 2006, there were 5.2 M beef cows while in 2020, there were only 3.6 M (Statistics Canada, 2020[7]). Consistent with this decline has been the conversion of land from pasture and perennial forages to annual cropland, amounting to 3.3 M ha between 2006 and 2016. The pasture and forage lands are important to support biodiversity of the agroecosystem and provides a sustainable land use for much marginal and fragile land that is prone to degradation as cropland. The pasture and forage land also contains large SOC stocks that are partially lost in the decades following the conversion to cropland. There are many drivers to the decline in beef herd but generally producers do not see as much value to them from producing beef compared with crop production on the land in pasture and forage.

There is an opportunity to reduce the magnitude of the decline of grazing and forage land by adopting beef production systems that require more pasture and forage so that there is less converted to cropland. This opportunity to use pasture more extensively in beef feeding is best suited to intensive rotational grazing with appropriate legume-grass pastures as that provides the best match over the grazing season with the nutritional needs of growing cattle. Optimal pasture-based feeding as part of the finishing feeding phase that uses radio-frequency identification (RFID) controlled access to supplemental grain on an animal-by-animal basis would make that approach more effective and efficient.

Liang et al. (2020) related the loss of soil C to the decline in cattle numbers. Each animal lost was associated with a C loss amounting to 2600 kg CO_2 in eastern Canada and 1700 kg CO_2 in western Canada. Of course, cattle are large GHG emitters, particularly CH_4 but also N_2O from their manure. The GHG emissions for SOC loss averaged 62% of the direct emission change from the drop in cattle population.

To evaluate the effect of the beef system, we used the Agriculture and Agri-Food Holos model to evaluate the effect of increasing use of pasture for cattle. We had two scenarios, one with backgrounding and finishing on barley and barley silage, and the other on alfalfa-grass hay, pasture, with final finishing on barley and alfalfa-grass hay. Table 3.8 shows the results for a hypothetical site in western Manitoba (values for conventional system from (Beauchemin et al., 2011) while those for grass/forage intensive adapted from Manitoba Forage and Grass Association[8]. The greater need for forage and pasture conserves that land from conversion to cropland. The avoided emissions were calculated from factors provided by the Climate Action Reserve protocol[9] for avoided grassland conversion.

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[7] https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210013001

[8] https://www.agrireseau.net/bovinsboucherie/documents/1_Forage_Finished_Beef_Final_Sept_7_e-book[1].pdf and https://static1.squarespace.com/static/5c6d9be4797f740e645a4310/t/5e25b69b5c97ae22c798107b/1579529883868/backgrounding_calves_with_manitoba_forage.pdf

[9] http://www.climateactionreserve.org/how/protocols/canada-grassland/

Without the avoided emissions, increased use of pasture increases GHG emissions because of greater emissions from enteric fermentation. However, with those avoided emissions included, there are fewer emissions for the same amount of beef produced with the more forage and pasture intensive system.

Table 3.8: Estimated emissions for conventional grain-based beef feeding and more forage and grain intensive beef feeding system for 1000 heifers and 1200 steers starting calf weight of 530 lb in western Manitoba.

	----------- Emission tonne CO_2e/yr ------------------					Acres	Emission tonne CO_2e/yr	
Feeding System	Enteric CH_4	Manure CH_4	Direct N_2O	Indirect N_2O	Total Emission	Additional forage&pasture land needed	Avoided Emissions	Net emissions
Backgrounding on finishing on barley and barley silage	2602	862	423	127	4014	0	0	4014
Backgrounding on alfalfa-grass hay and pasture, final finish in feedlot on alfalfa-grass hay and barley	5156	1355	1089	245	7846	6535	6490	1356

A complete life cycle assessment would be necessary to refine results for particular situations but, importantly, the largest omission in the analysis done for this study is the GHG emissions for the grain and grain crop silage that is displaced by forage and pasture. However, the GHG footprint of alfalfa-based forage/pasture is much lower than either grain or grain crop silage (Desjardins et al., 2019), so that displacement adds to the GHG advantage of using more pasture and forage in beef feeding systems.

Policies and programs to change feeding systems is beyond the scope of this study, but this analysis of more advanced and intensive rotational grazing supports increased use of pasture for feed and thereby reduces or reverses the conversion of grazing land to cropland without increasing net GHG emissions.

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4. Conserving trees and wetlands on agricultural lands in Canada for Climate Change mitigation

Introduction

Every year, between 2010 and 2017, there was an annual average of 12 000 ha of forests converted to agriculture (Drever et al. 2021, accepted). Conversion of treed areas to cropland for narrow linear trees (shelterbelts and hedgerows) and areas less than 1 ha (e.g., trees associated with small wetlands) are not included in this estimate. Nevertheless, these tree removals that are not counted as deforestation in inventory are still important. For example, from 2008 to 2016, 2,500 km of shelterbelts were removed in Saskatchewan, representing an estimated loss of C of 1.2 Mt CO_2e (Ha et al. 2019).

Drever et al. (2021, accepted) estimated that there are 356 000 ha of wetlands on the prairies that are threatened by immediate conversion to cropland.

Both the trees and the wetlands in the agricultural landscape are extremely important for biodiversity preservation as they provide important habitat for many organisms. Wetlands and trees are also important moderators of hydrology and reduce risk of downstream flooding (Dumanski et al. 2015; Pattison-Williams 2018). Further, once converted to cropland that land area takes on all the environmental disadvantages of cropland including loss of soil health and loss of damaging nutrients and pesticides to the larger environment.

Retaining existing trees and wetlands on the agricultural landscape by encouraging their protection is a certain and relatively simple means to achieve large environmental benefits.

Methods of Estimating Greenhouse Gas Emissions and Carbon Sequestration

Trees

Clearing the trees releases massive amounts of CO_2 to the atmosphere and deforestation is a major cause of climate change globally. Clearing trees also their continued removal sequestration of CO_2 and sequestering that carbon in biomass and soils. However, trees also reduce the land surface reflectance (i.e., albedo) and this cause radiative forcing that cause warming. For example, Drever et al. 2021 (accepted)) includes additional warming from trees equivalent to emission to 1.95 Mg CO_2e ha^{-1}. The change in albedo will be much higher for evergreen trees. Albedo effects on global warming are not currently included in National Inventory Report. For policy analysis regarding forest management for climate change mitigation needs to consider albedo effects (Matthies and Valsta 2016. Mykleby et al. 2017). For this study, we considered the cooling from deforestation due to albedo change was balanced by lost sequestration of the forest. We also assumed that there are no anthropogenic N_2O emissions from the soils under trees since there is no direct supplemental N fertilization of the forest (IPCC 2006).

Based on the National Inventory report (ECCC, 2020), the average immediate emissions from tree clearing to agriculture is 75 Mg CO_2e ha^{-1} in year of conversion with residual emissions from loss of SOC and residual tree biomass decomposition over 20 years averages 5 Mg CO_2e ha^{-1} yr^{-1}.

Wetlands

The emissions for either existing or for draining and converting wetlands to cropland are not yet included in the National Inventory Report. However, the National Inventory Report must adhere to the principle of completeness so there are both demands and actions to include these emissions before 2030.

The average existing wetland in agricultural land in Canada emits 198 kg CH_4 per hectare, amounting to 0.495 tonne CO_2e ha^{-1} yr^{-1} (Climate Action Reserve 2020). Wetlands also act as C sinks in their sediments and in surrounding trees and shrubs, but the amount is site dependent, so it is difficult to estimate (Kayranli et al. 2010). Similar to the assumption for forests, we neglected the loss of ongoing sequestration as an allowance for any decrease in radiative forcing from an increase in surface albedo after conversion to cropland. Drever et al. (2021 (accepted)) estimated the loss of SOC from conversion of wetland as 89 Mg C ha^{-1} (326 Mg CO_2e ha^{-1}) over 20 years, or 16.3 Mg CO_2e ha^{-1} yr^{-1} for 20 years. Draining wetlands and converting them to cropland results in large C stock losses as CO_2. The net emission over 20 years is thus 15.8 Mg CO_2e ha^{-1} yr^{-1}

Cropland Greenhouse Gas Emissions after Conversion

We estimated the total N_2O and direct CO_2 emissions of cropland in Table 4.1 (Climate Action Reserve 2020). The fossil fuel energy for field operations was estimated based on values from Dyer and Desjardins (2005) based on areas of different tillage systems for 2016. The embodied GHG emissions for inputs such as fertilizer and herbicides were not included.

Table 4.1: Summary of emissions from cropland.

Type	Zone* Moist and warm Canada	Dry Canada	Moist and cool Canada
	----------------	Mg $CO_2e\ ha^{-1}\ yr^{-1}$	------------
N_2O	0.94	0.25	0.52
Direct soil amendments**	0.026	0.013	0.018
Farm machinery	0.19	0.10	0.12
Total	1.26	0.37	0.66

*moist and warm is mixed wood plains, Atlantic maritime, and Pacific maritime ecozones, dry Canada is the Brown and Dark Brown soil zones of Alberta and Saskatchewan, and moist and cool Canada is all the remainder of Canada including subhumid western Canada and agricultural land north of warm and moist Canada
**direct emissions from lime and urea

Greenhouse Gas Emission Reduction from Avoided Conversion

The total avoided emissions, expressed as CO_2e over 20 years, are the sum of the emissions associated with the conversion and that of the avoided emissions had that land became cropland (Table 4.2). We assumed that tree clearing would be in proportion to the relative areas for these zones, 80% occurring in moist and cool and 20% in moist and warm. Most of the wetland conversion is expected in moist and cool Canada.

Table 4.2: Avoided emissions for one hectare of avoided conversion (Mg CO2e)

Land use	Avoided conversion over 20 years	Avoided cropland emissions over 20 years	Total over 20 years
Trees	175	16	191
Wetlands	317	13	330

Avoided Conversion Scenarios

We considered a program of conservation of 13360 ha a year for 20 years, consisting of 2560 ha of trees and 10800 ha of wetlands. The wetland conservation is emphasized because expected to have larger total environmental benefits per ha than tree conservation. Potentially, this rate of conservation could protect a significant portion of the land that is expected to be converted to agriculture over the next 20 years.

The GHG emission reduction potentials from conservation depends on the ability to correctly identify land that is most likely to be converted to cropland. A mistake in this identification protects land that would remain in wetland and trees without any intervention. The knowledge and capacity to determine the risk of conversion (i.e., the likelihood that the wetlands and trees will soon be converted to cropland) already exists. For purposes of taxing land, the value of the land is assessed based on its highest value use rather than its actual use. In agricultural landscapes, the highest value use is generally for cropland so the market value of the land for tax assessment purposes is based on cropland even if the current use is in trees or wetland. The market value reflects the net present value of future net returns for that land. Hence, once the increase in the value of the land with conversion exceeds the costs for conversion, then there is a compelling economic incentive to convert the wetlands and trees to cropland whether that decision is made for long-term production in the existing farming operation or for land market value. The greater the increase in value of land with conversion to cropland, the greater the potential likelihood of that conversion. Importantly, bidders who want to purchase that land will factor in the financial benefit of conversion to cropland and so those who plan to convert such land immediately will be able to outbid those who want to retain wetland and/or trees. Market forces continually induce conversion of forests and wetlands to cropland when only the private value of land is included. Therefore, a payment for the public value of conservation of those lands is needed to overcome those market forces.

Although valuable for land-use planning, evaluating all land for its relative likelihood for conversion would be very expensive. One challenge is that conventional assessment of land for tax purposes is on the basis of all land within the land tenure boundaries whereas, for this conservation purpose, the assessment has to be for actual specific portions that are in trees or wetlands within those larger properties. However, evaluating conversion likelihood for only the particular land that is volunteered for inclusion in a payment program for conservation is more feasible. Therefore, policies that target conservation of land by engaged landowners are particularly attractive.

There are two potential mistakes that effect the estimated avoided emissions from conservation. One is that the conserved land that was not going to be converted within the 20 years. The other is that land that will be converted within 20 years, but it would be converted later than the year it was protected. In the latter case, the avoided emissions only occur for a portion of the 20 years of conservation. Timing the protection to coincide with the year that land would be converted is difficult since it depends on other farmer-specific factors such as desire and availability of capital to finance the land conversion. This interval between protection and likely time of conversion is less important for conversion of trees to agricultural land since nearly 40% of total emissions over 20 years occur in the year of conversion. Also, if the protection agreement is renewed the effect of interval becomes less important, albeit with the additional cost of renewal on conservation protection. However, renewal of conservation protection does not reduce the effect of selecting land for protection that is not likely to be converted other than if such land becomes more likely for conversion during the extended protection period. Table 4.3 shows the effect of making the mistakes of estimating the interval between year of conservation and the year the land would have actually been converted. The conserving land that will not be converted is directly proportion to the % of land correctly selected. If 60% of the land selected would be converted in the 20-year period, the values in Table 4.3 should be multiplied by 60%.

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Table 4.3: Effect of mean interval between conservation and potential conversion on avoided emissions.

Interval between year of conservation and year of conversion	Avoided emissions over 20 years (Mt CO_2e) of land conserved in 2021 for 20 years	Avoided emissions in 2030 (Mt CO_2e/yr) for the conservation program implemented 2021-2030
0	4.1	2.1
1	3.9	1.9
3	3.5	1.5
5	3.1	1.2

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5. Summary and Conclusions

Four practices were assessed for their potential to reduce greenhouse gas emission and sequester carbon in agricultural systems together accounting for 17.6 Mt CO_2e yr^{-1} in 2030 (Table 5.1).

Table 5.1:Summary of GHG emissions reduction potential in 2030 for the four programs evaluated in this report.

	(Mt CO2e yr^{-1} in 2030)
Improved Nitrogen Management	3.3
Cover Crops	8.6
Rotational Grazing	3.6
Trees and Wetlands	2.1

Improved Nitrogen Management

Improved nitrogen management has significant potential to reduce annual N_2O emissions associated with the use of nitrogen fertilizer. Industry-led initiatives such as 4R nutrient management have made significant progress in raising awareness of the need for more efficient nitrogen management but have not necessarily resulted in that outcome. The adoption of basic and intermediate levels of 4R nitrogen management in combination with a reduction in total fertilizer N use per hectare across five of the major N requiring crops (canola, corn, spring wheat, winter wheat, and potato) could result in an annual reduction in direct and indirect N_2O emissions of 3.3 Mt of CO_2e y^{-1}. In addition, the reduction in N fertilizer use would also result in a reduction in CO_2 emissions associated with fertilizer manufacture an additional reduction of (271.3 kt CO_2e yr^{-1} in 2030). These reductions could be achieved through subsidy of independent agronomists to provide 4R recommendations coupled with a subsidy in the measurement of nitrate remaining in the soil in the fall to confirm and document the success of the program in increasing nitrogen use efficiency and thereby reduce N_2O emissions and other N losses such as nitrate leaching and ammonia emissions.

Cover Crops

The potential benefits of cover crops vary greatly regionally. There is also important variation in benefits within the large agricultural region of the Prairies. There are many important unknowns, the short- and long-term benefits of cover crops and exact effects on GHG fluxes, that make it difficult to accurately estimate the adoption and full benefits of cover crops. Research is desperately needed to address these knowledge gaps. Cover crops are most favourable in coastal regions (excluding Newfoundland and Labrador) and southern Ontario and Quebec. In this region modest support is expected to be able to increase cover crop adoption appreciably, especially in the first 3-5 years when private economic benefits are not yet accrued by the farmer. Cover crops are least favoured in the semiarid region of the Prairies. Although there is some good potential for cover crops in the remainder of Canada (northern eastern Canada and the subhumid prairie region), fully realizing that potential will require research, development, and demonstration to improve cover crop technology and awareness for more challenging Canadian conditions. The potential greenhouse-gas reduction from cover crops is significant.

Rotational Grazing

There is sufficient evidence to provide general estimates of the SOC increase with adoption of rotational grazing in Canada. There is also evidence of a minor reduction in emissions associated with enteric fermentation due to better forage quality. With the right support for infrastructure and planning requirements of more advanced and intensive rotational grazing, there is a feasible potential to reduce emissions by 3.6 Mt CO_2e per year in 2030 relative to current practices. Although nearly half of Canada's grazing land is in semiarid prairies, this area only accounted for 11% of estimated emission reduction. The subhumid prairies are estimated to contribute fully 2.5 Mt CO_2e of overall reduction. Rotational grazing has important co-benefits of maintaining and increasing biodiversity. Adoption of rotational grazing is consistent with increased use of more pasture for finishing beef cattle and that practice can reduce the conversion of grazing land to cropland and thereby avoid the greenhouse gas emissions and other negative environmental consequences of that conversion.

Trees and Wetlands

Retaining existing trees and wetlands on the agricultural landscape by ensuring their conservation is a relatively simple but effective means to achieve large environmental benefits. The greenhouse gas emission reduction from annual conservation of 13360 ha of wetlands and trees that will, in all likelihood, be soon converted to cropland could prevent 44 Mt of CO_2e emissions over 20 years.

Appendix A - Definition of Improved Nitrogen (4R) Management Suites

Spring Wheat Assumptions

Reduction in N_2O emissions were calculated by soil landscape polygon and averaged by province.

BAU N Fertilizer use:
2025 1.1 x 2017 Prairies, Rest of Canada constant at 2017 rates
2030 1.19 x 2017 Prairies, Rest of Canada constant at 2017 rates

Reduction in N fertilizer use as part of 4R implementation: Basic 0%; Intermediate 10%; Advanced 20%

2017 No 4R 20%; Basic 20%; Intermediate 20%; Advanced 20%
2025: No 4R 20%; Basic 15%; Intermediate 15%; Advanced 40%
2030: No 4R 20%; Basic 10%; Intermediate 10%; Advanced 60%

4R Implementation

Basic (N_2O Reduction modifier = 0.85)

Source: Ammonium-based fertilizer N sources, Ammonium based NPS sources (MAP, DAP, APP, AS) allowed for fall or spring.

Rate: Optimize N Rate by: Setting field specific N rates. Account for all fertilizer N and available N from previous legume crops in total application. Apply N following 4R plan using annual soil testing and/or N balance. N rates are based on provincial guidelines (as a reference). Consider probabilities for weather variations when setting rates.

Time: Apply fertilizer N in spring before or at seeding; or apply fertilizer N in fall after soil cools (below 10 o C for 3 consecutive days and not before Oct. 10) or split application between fall after soil cools and spring before or at seeding or in season (at most 1/3 of N applied). UAN not eligible for fall application.

Place: Apply in subsurface bands/injection. Surface application in season allowed (at most 1/3 of the N)

Intermediate (N_2O Reduction modifier = 0.75)

Source: Same as Basic, plus use enhanced efficiency fertilizers (nitrification inhibitors (NI), double inhibitors (NI and Urease inhibitors (UI)) or controlled release (CR)) in high moisture, high risk situations

Rate: Optimize N Rate by: The same as Basic, plus apply N according to sub field zones using qualitative estimates of field variability (landscape position, soil variability). Where used, adjust rates to account for enhanced efficiency sources (eg. UI, NI)
Time: Same as Basic
Place: Apply in subsurface bands/injection. Broadcast application utilizing double inhibitors (NI and UI)

Advanced (N_2O Reduction modifier = 0.65)
Source: Same as Basic, plus enhanced efficiency fertilizers (nitrification inhibitors (NI), double inhibitors (NI and Urease inhibitors (UI)) or controlled release (CR)) in all situations
Rate: Same as Basic but setting subfield zones and applying specific N rates according to quantified field variability using digitized zone maps, zone soil sampling, remote sensing (advanced variable rate). Complement with in season crop monitoring.
Time: Same as Basic and Intermediate
Place: Apply in subsurface bands/injection. No broadcast application

Spring Wheat (Cumulative reductions)

	2017			2025			2030		
	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	1064	5280	9354	798	4846	11616	532	4413	13879
AB	31836	157434	278788	26265	159066	379869	18942	156815	490142
SK	53255	262441	464526	43935	265330	631421	31687	261774	813380
MB	29529	146218	258969	24362	147698	353184	17570	145566	455988
ON	1051	5267	9343	789	4827	11677	526	4386	14012
QC	2788	14022	24885	2091	12839	31186	1394	11657	37486
NB	278	1399	2482	209	1281	3110	139	1163	3739
NS	30	150	266	22	137	333	15	125	401
PE	445	2239	3974	334	2050	4982	222	1861	5990
NF	0	1	2	0	1	3	0	1	3
N2O Reduction (kg N2O-N)									
Prairies	114620	566093	1002283	94562	572095	1364474	68199	564155	1759510
Rest of Canada	5656	28358	50306	4242	25981	62908	2828	23605	75510
N2O Reduction (kt CO2e)									
Prairies	53.7	265.1	469.4	44.3	267.9	639.0	31.9	264.2	824.0
Rest of Canada	2.6	13.3	23.6	2.0	12.2	29.5	1.3	11.1	35.4

Spring Wheat (Cumulative reductions as a result of reduced N fertilizer Manufacture)

	2017			2025			2030		
N Fertilizer Manufacture (kT CO2e)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	0.0	0.3	0.6	0.0	0.2	1.2	0.0	0.1	1.8
AB	0.0	12.7	27.4	0.0	9.5	54.7	0.0	6.3	82.1
SK	0.0	26.8	58.0	0.0	20.1	115.9	0.0	13.4	173.9
MB	0.0	9.9	21.5	0.0	7.5	43.0	0.0	5.0	64.5
ON	0.0	0.2	0.4	0.0	0.1	0.8	0.0	0.1	1.2
QC	0.0	0.5	0.9	0.0	0.3	1.8	0.0	0.2	2.7
NB	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.3
NS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PE	0.0	0.1	0.1	0.0	0.1	0.3	0.0	0.0	0.4
NF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N Fertilizer Manufacture (kT CO2e)									
Prairies	0.0	49.4	106.9	0.0	37.0	213.7	0.0	24.7	320.6
Rest of Canada	0.0	1.1	2.1	0.0	0.8	4.2	0.0	0.5	6.4

Spring Wheat (per hectare reductions)

	2017			2025			2030		
N2O Reduction (g N2O-N/ha)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	62.69	311.17	551.29	47.02	285.62	684.62	31.35	260.07	817.95
AB	11.50	56.88	100.72	9.49	57.47	137.24	6.84	56.65	177.08
SK	12.39	61.04	108.05	10.22	61.72	146.87	7.37	60.89	189.19
MB	27.88	138.04	244.48	23.00	139.44	333.43	16.59	137.42	430.48
ON	45.01	225.53	400.04	33.76	206.66	499.98	22.51	187.79	599.92
QC	37.57	189.00	335.43	28.18	173.07	420.36	18.79	157.13	505.29
NB	99.88	502.40	891.61	74.91	460.04	1117.32	49.94	417.68	1343.03
NS	35.78	180.08	319.61	26.83	164.87	400.70	17.89	149.67	481.80
PE	39.00	196.30	348.40	29.25	179.73	436.80	19.50	163.15	525.20
NF	2.04	10.28	18.24	1.53	9.41	22.87	1.02	8.54	27.50
N2O Reduction (g N2O-N/ha y)									
Prairies	17.3	85.3	151.1	14.2	86.2	205.8	10.3	85.0	265.6
Rest of Canada	46.0	230.7	409.2	34.5	211.3	511.8	23.0	192.0	614.4
N2O Reduction (kg CO2e/ha y)									
Prairies	8.1	40.0	70.8	6.7	40.4	96.4	4.8	39.8	124.4
Rest of Canada	21.5	108.0	191.6	16.2	99.0	239.7	10.8	89.9	287.7

Canola Assumptions

Reduction in N_2O emissions were calculated by soil landscape polygon and averaged by province.

BAU N Fertilizer use:
2025 1.1 x 2017 Prairies, Rest of Canada constant at 2017 rates
2030 1.19 x 2017 Prairies, Rest of Canada constant at 2017 rates

Reduction in N fertilizer use as part of 4R implementation: Basic 0%; Intermediate 10%; Advanced 20%

2017 No 4R 20%; Basic 20%; Intermediate 20%; Advanced 20%
2025: No 4R 20%; Basic 15%; Intermediate 15%; Advanced 40%
2030: No 4R 20%; Basic 10%; Intermediate 10%; Advanced 60%

4R Implementation

Basic (N_2O Reduction modifier = 0.85)

Source: Ammonium-based fertilizer N sources, Ammonium based NPS sources (MAP, DAP, APP, AS) allowed for fall or spring.

Rate: Optimize N Rate by: Setting field specific N rates. Account for all fertilizer N and available N from previous legume crops in total application. Apply N following 4R plan using annual soil testing and/or N balance. N rates are based on provincial guidelines (as a reference). Consider probabilities for weather variations when setting rates.

Time: Apply fertilizer N in spring before or at seeding; or apply fertilizer N in fall after soil cools (below 10 o C for 3 consecutive days and not before Oct. 10) or split application between fall after soil cools and spring before or at seeding or in season (at most 1/3 of N applied). UAN not eligible for fall application.

Place: Apply in subsurface bands/injection. Surface application in season allowed (at most 1/3 of the N)

Intermediate (N_2O Reduction modifier = 0.75)

Source: Same as Basic, plus use enhanced efficiency fertilizers (nitrification inhibitors (NI), double inhibitors (NI and Urease inhibitors (UI)) or controlled release (CR)) in high moisture, high risk situations

Rate: Optimize N Rate by: The same as Basic, plus apply N according to sub field zones using qualitative estimates of field variability (landscape position, soil variability). Where used, adjust rates to account for enhanced efficiency sources (eg. UI, NI)

Time: Same as Basic

Place: Apply in subsurface bands/injection. Broadcast application utilizing double inhibitors (NI and UI)

Advanced (N_2O Reduction modifier = 0.65)
Source: Same as Basic, plus enhanced efficiency fertilizers (nitrification inhibitors (NI), double inhibitors (NI and Urease inhibitors (UI)) or controlled release (CR)) in all situations
Rate: Same as Basic but setting subfield zones and applying specific N rates according to quantified field variability using digitized zone maps, zone soil sampling, remote sensing (advanced variable rate). Complement with in season crop monitoring.
Time: Same as Basic and Intermediate
Place: Apply in subsurface bands/injection. No broadcast application

Canola (Cumulative reductions)

	2017			2025			2030		
N2O Reduction (kg N2O-N)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	1052	5222	9251	789	4793	11486	526	4365	13721
AB	36939	182816	323767	30475	184684	441400	21979	182038	569747
SK	69914	344941	610646	57679	348664	830720	41599	343902	1070708
MB	35076	173673	307593	28937	175433	419485	20870	172902	541577
ON	370	1852	3285	277	1698	4104	185	1543	4923
QC	570	2865	5084	428	2624	6365	285	2383	7645
NB	40	204	361	30	186	453	20	169	545
NS	0	0	0	0	0	0	0	0	0
PE	0	0	0	0	0	0	0	0	0
NF	0	0	0	0	0	0	0	0	0
N2O Reduction (kg N2O-N)									
Prairies	141928	701430	1242007	117091	708780	1691606	84447	698842	2182032
Rest of Canada	2033	10143	17982	1525	9302	22408	1017	8460	26834
N2O Reduction (kt CO2e)									
Prairies	66.5	328.5	581.6	54.8	331.9	792.2	39.5	327.3	1021.8
Rest of Canada	1.0	4.7	8.4	0.7	4.4	10.5	0.5	4.0	12.6
N Manufacture	0.0	51.4	102.9	0.0	42.4	226.1	0.0	30.6	366.7

Canola (Cumulative reductions as a result of reduced N fertilizer Manufacture)

	2017			2025			2030		
N Fertilizer Manufacture (kT CO2e)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	0.0	0.3	0.6	0.0	0.2	1.2	0.0	0.1	1.8
AB	0.0	13.4	29.0	0.0	10.0	57.9	0.0	6.7	86.9
SK	0.0	30.8	66.7	0.0	23.1	133.4	0.0	15.4	200.1
MB	0.0	11.8	25.6	0.0	8.9	51.2	0.0	5.9	76.8
ON	0.0	0.1	0.1	0.0	0.1	0.3	0.0	0.0	0.4
QC	0.0	0.1	0.2	0.0	0.1	0.4	0.0	0.0	0.6
NB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

N Fertilizer Manufacture (kT CO2e)									
Prairies	0.0	56.1	121.3	0.0	42.0	242.6	0.0	28.0	363.8
Rest of Canada	0.0	0.5	0.9	0.0	0.4	1.9	0.0	0.2	2.8

Canola (per hectare reductions)

	2017			2025			2030		
N2O Reduction (g N2O-N/ha)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	24	119	210	18	109	261	12	99	312
AB	13	66	117	11	67	160	8	66	207
SK	14	69	121	11	69	165	8	68	213
MB	27	135	240	23	137	327	16	135	423
ON	21	106	188	16	97	235	11	88	282
QC	39	196	348	29	180	436	20	163	524
NB	91	458	812	68	419	1018	45	380	1224
NS									
PE									
NF									
N2O Reduction (g N2O-N/ha y)									
Prairies	18	90	160	15	91	218	11	90	281
Rest of Canada	44	220	390	33	201	488	22	183	585
N2O Reduction (kg CO2e/ha y)									
Prairies	9	42	75	7	43	102	5	42	131
Rest of Canada	20	103	182	15	94	228	10	86	274

Potato Assumptions (Prairies)

Reduction in N_2O emissions were calculated by soil landscape polygon and averaged by province.
It is assumed that the majority of potato production is under irrigation.

BAU N Fertilizer use:
2025 1.1 x 2017 Prairies, Rest of Canada constant at 2017 rates
2030 1.19 x 2017 Prairies, Rest of Canada constant at 2017 rates

Reduction in N fertilizer use as part of 4R implementation: Basic 0%; Intermediate 10%; Advanced 20%

2017 No 4R 20%; Basic 20%; Intermediate 20%; Advanced 20%
2025: No 4R 20%; Basic 15%; Intermediate 15%; Advanced 40%
2030: No 4R 20%; Basic 10%; Intermediate 10%; Advanced 60%

4R Implementation

Basic (N_2O Reduction modifier = 0.85)

Source: Any N fertilizer with guaranteed analysis.
Rate: Apply based on nitrogen balance or provincial guidelines for attainable yield. Set field specific rates based on previous yield history and soil types. Adjust for variety following provincial guidelines.
Time: Apply nitrogen in spring before or at seeding. No N application on frozen soil and/or snow-covered ground.
Place: Broadcast and incorporate. Consider using enhanced efficiency fertilizer in cases where incorporation is not possible following surface application.

Intermediate (N_2O Reduction modifier = 0.80)

Source: Same as Basic, plus use of enhanced efficiency fertilizers (nitrification inhibitors, double inhibitors (urease and nitrification), or controlled release) should account for at least 33% of total N budget
Rate: Same as Basic, plus adjust N rates based on estimates of residual nitrogen in combination with estimates of other soil supply sources (mineralization, previous pulse or other legume crops). Build N rate strategy based on well-developed field management zones adjusting N rates according to estimates of field variability.
Time: Same as Basic, plus split nitrogen between before or at seeding and one or more in season applications.
Place: Same as Basic

Advanced (N_2O Reduction modifier = 0.70)
Source: Same as Intermediate, plus use of enhanced efficiency fertilizers (nitrification inhibitors, double inhibitors (urease and nitrification), or controlled release) should account for at least 50% of total N budget.
Rate: Same as Intermediate, plus apply N according to quantified field variability using digitized soil maps (advanced variable rate). Monitor in season and/or post season N use using technologies such as crop sensors, satellite or UAV imagery, crop nitrogen demand modelling, field scouting, and petiole testing.
Time: Same as Intermediate
Place: Same as Intermediate

Potato Assumptions (Rest of Canada)

Reduction in N_2O emissions were calculated by soil landscape polygon and averaged by province.
It is assumed that the majority of potato production is rainfed.

BAU N Fertilizer use:
2025 1.1 x 2017 Prairies, Rest of Canada constant at 2017 rates
2030 1.19 x 2017 Prairies, Rest of Canada constant at 2017 rates

Reduction in N fertilizer use as part of 4R implementation: Basic 0%; Intermediate 10%; Advanced 20%

2017 No 4R 20%; Basic 20%; Intermediate 20%; Advanced 20%
2025: No 4R 20%; Basic 15%; Intermediate 15%; Advanced 40%
2030: No 4R 20%; Basic 10%; Intermediate 10%; Advanced 60%

4R Implementation

Basic (N_2O Reduction modifier = 0.95)
Source: Any N fertilizer with guaranteed analysis.
Rate: Apply based on nitrogen balance or provincial guidelines for yield goals. Set field specific rates based on previous yield history and soil types. Adjust for variety following provincial guidelines.
Time: Apply nitrogen in spring before or at seeding. No N application on frozen soil and/or snow-covered ground.

Place: Broadcast and incorporate. Consider using enhanced efficiency fertilizer in cases where incorporation is not possible following surface application.

Intermediate (N_2O Reduction modifier = 0.90)
Source: Same as Basic, plus use of enhanced efficiency fertilizers (nitrification inhibitors, double inhibitors (urease and nitrification), or controlled release) should account for at least 33% of total N budget
Rate: Same as Basic, plus adjust N rates based on estimates of residual nitrogen in combination with estimates of other soil supply sources (mineralization, previous pulse or other legume crops). Build N rate strategy based on well-developed field management zones adjusting N rates according to estimates of field variability.
Time: Same as Basic, plus split nitrogen between before or at seeding and one or more in season applications.
Place: Same as Basic

Advanced (N_2O Reduction modifier = 0.80)
Source: Same as Intermediate, plus use of enhanced efficiency fertilizers (nitrification inhibitors, double inhibitors (urease and nitrification), or controlled release) should account for at least 50% of total N budget.
Rate: Same as Intermediate, plus apply N according to quantified field variability using digitized soil maps (advanced variable rate). Monitor in season and/or post season N use using technologies such as crop sensors, satellite or UAV imagery, crop nitrogen demand modelling, field scouting, and petiole testing.
Time: Same as Intermediate
Place: Same as Intermediate

Potato (Cumulative reductions)

		2017			2025			2030	
N2O Reduction (kg N2O-N)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	19	230	452	14	219	532	9	208	612
AB	191	883	1691	157	904	2216	113	904	2783
SK	35	163	309	29	167	405	21	167	509
MB	707	3284	6328	583	3357	8293	420	3355	10414
ON	192	2371	4664	144	2259	5481	96	2147	6298
QC	354	4391	8640	266	4179	10195	177	3967	11750
NB	604	7482	14723	453	7120	17375	302	6759	20027
NS	17	208	409	13	198	483	8	188	557
PE	549	6803	13386	411	6474	15800	274	6144	18214
NF	2	24	47	1	23	55	1	21	63
N2O Reduction (kg N2O-N)									
Prairies	932	4330	8328	769	4427	10915	555	4426	13706
Rest of Canada	1736	21508	42321	1302	20471	49922	868	19434	57522
N2O Reduction (kt CO2e)									
Prairies	0.4	2.0	3.9	0.4	2.1	5.1	0.3	2.1	6.4
Rest of Canada	0.8	10.1	19.8	0.6	9.6	23.4	0.4	9.1	26.9
N Manufacture	0.0	1.2	2.4	0.0	0.9	4.9	0.0	0.6	7.6

Potato (Cumulative reductions as a result of reduced N fertilizer Manufacture)

	2017			2025			2030		
N Fertilizer Manufacture (kT CO2e)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
AB	0.0	0.1	0.2	0.0	0.1	0.5	0.0	0.1	0.7
SK	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1
MB	0.0	0.2	0.5	0.0	0.2	1.1	0.0	0.1	1.6
ON	0.0	0.1	0.2	0.0	0.1	0.4	0.0	0.1	0.6
QC	0.0	0.2	0.3	0.0	0.1	0.7	0.0	0.1	1.0
NB	0.0	0.3	0.6	0.0	0.2	1.2	0.0	0.1	1.8
NS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PE	0.0	0.3	0.5	0.0	0.2	1.1	0.0	0.1	1.6
NF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N Fertilizer Manufacture (kT CO2e)									
Prairies	0.0	0.4	0.8	0.0	0.3	1.6	0.0	0.2	2.4
Rest of Canada	0.0	0.9	1.7	0.0	0.6	3.4	0.0	0.4	5.1

Potato (per hectare reductions)

	2017			2025			2030		
N2O Reduction (g N2O-N/ha)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	6	78	154	5	74	181	3	71	208
AB	9	40	77	7	41	101	5	41	127
SK	13	59	112	10	60	146	8	60	184
MB	26	121	234	22	124	307	16	124	385
ON	14	172	338	10	163	397	7	155	456
QC	21	256	504	16	244	595	10	232	686
NB	33	410	806	25	390	951	17	370	1097
NS	24	298	586	18	283	691	12	269	797
PE	16	203	400	12	193	472	8	184	544
NF	14	172	339	10	164	400	7	156	461
N2O Reduction (g N2O-N/ha y)									
Prairies	16	74	141	13	75	185	9	75	232
Rest of Canada	18	227	447	14	216	527	9	205	607
N2O Reduction (kg CO2e/ha y)									
Prairies	7	34	66	6	35	87	4	35	109
Rest of Canada	9	106	209	6	101	247	4	96	284

Corn Assumptions

Reduction in N_2O emissions were calculated by soil landscape polygon and averaged by province.

BAU N Fertilizer use:
2025 1.1 x 2017 Prairies, Rest of Canada constant at 2017 rates
2030 1.19 x 2017 Prairies, Rest of Canada constant at 2017 rates

Reduction in N fertilizer use as part of 4R implementation: Basic 0%; Intermediate 10%; Advanced 20%

2017 No 4R 20%; Basic 20%; Intermediate 20%; Advanced 20%
2025: No 4R 20%; Basic 15%; Intermediate 15%; Advanced 40%
2030: No 4R 20%; Basic 10%; Intermediate 10%; Advanced 60%

4R Implementation

Basic (N_2O Reduction modifier = 0.85)

Source: Ammonium based formulation with guaranteed analysis, Ammonium based NPS sources (MAP, DAP, APP, AS) allowed.

Rate: Optimize N Rate by: Setting field specific N rates considering field specific yield history and soil types in relation to yield potential of other fields on farm and in region. Account for all fertilizer N and available N from previous legume crops in total application. Apply based on N balance or provincial guidelines (e.g., OMAFRA tables). Consider probabilities for weather variations when setting rates.

Time: Apply fertilizer N in spring before or at seeding. No N application (fertilizer or manure) on frozen soil and/or snow-covered ground.

Place: Apply in subsurface bands/injection. Side band at seeding Broadcast and incorporate within 48 hours

Intermediate (N_2O Reduction modifier = 0.75)

Source: Same as Basic, plus use enhanced efficiency fertilizers (nitrification inhibitors (NI), double inhibitors (NI and Urease inhibitors (UI)) or controlled release (CR)) make up at least 33% of total N total N application, targeted to high moisture, high risk situations.

Rate: Same as Basic. Set zone rather than field N rates, based on estimates of residual N + mineralization (e.g. soil test or predictions from models)
Time: Same as Basic
Place: Same as Basic, plus broadcast and incorporate within 24 hours, or surface application using NI and UI

Advanced (N_2O Reduction modifier = 0.65)
Source: Same as Intermediate, plus enhanced efficiency fertilizers make up at least 50% of total N application, targeted to high moisture, high risk situations.
Rate: Same as Intermediate, plus variable rate based on digitized zone maps. In field sensors of residual N. In season crop monitoring. In season or post season assessment of N supply.
Time: Same as Intermediate, plus split application in season (at least 1/3 of N as sidedress)
Place: Same as Intermediate, plus surface application limited to in season using surface banded with NI and UI.

Corn (Cumulative reductions)

	2017			2025			2030		
N2O Reduction (kg N2O-N)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	213	1067	2364	160	978	2600	107	889	2836
AB	1132	5591	12252	934	5650	14772	673	5571	17381
SK	887	4375	9571	732	4423	11533	528	4363	13565
MB	5912	29277	64292	4877	29572	77563	3518	29145	91311
ON	46750	234013	518422	35062	214468	570112	23375	194922	621801
QC	25611	128862	286654	19208	117989	315633	12806	107117	344611
NB	514	2587	5753	386	2369	6334	257	2151	6916
NS	802	4038	8984	602	3697	9893	401	3356	10803
PE	466	2343	5214	349	2145	5742	233	1948	6269
NF	0	1	3	0	1	4	0	1	4
N2O Reduction (kg N2O-N)									
Prairies	7931	39242	86116	6543	39645	103868	4719	39079	122256
Rest of Canada	74356	372911	827396	55767	341647	910318	37178	310383	993240
N2O Reduction (kt CO2e)									
Prairies	3.7	18.4	40.3	3.1	18.6	48.6	2.2	18.3	57.3
Rest of Canada	34.8	174.6	387.5	26.1	160.0	426.3	17.4	145.3	465.1

Corn (Cumulative reductions as a result of reduced N fertilizer Manufacture)

	2017			2025			2030		
N Fertilizer Manufacture (kT CO2e)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	0.0	0.1	0.2	0.0	0.0	0.3	0.0	0.0	0.4
AB	0.0	0.5	2.2	0.0	0.4	2.8	0.0	0.3	3.4
SK	0.0	0.4	1.8	0.0	0.3	2.3	0.0	0.2	2.7
MB	0.0	2.0	8.6	0.0	1.5	10.7	0.0	1.0	12.8
ON	0.0	8.8	35.3	0.0	6.6	44.1	0.0	4.4	52.9
QC	0.0	4.1	16.4	0.0	3.1	20.5	0.0	2.1	24.6
NB	0.0	0.1	0.3	0.0	0.1	0.4	0.0	0.0	0.5
NS	0.0	0.1	0.5	0.0	0.1	0.6	0.0	0.1	0.8
PE	0.0	0.1	0.3	0.0	0.1	0.4	0.0	0.0	0.4
NF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N Fertilizer Manufacture (kT CO2e)									
Prairies	0.0	2.9	12.6	0.0	2.2	15.8	0.0	1.5	18.9
Rest of Canada	0.0	13.3	53.1	0.0	10.0	66.4	0.0	6.6	79.6

Corn (per hectare reductions)

	2017			2025			2030		
N2O Reduction (g N2O-N/ha)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	19	94	207	14	86	228	9	78	249
AB	21	102	224	17	103	271	12	102	318
SK	28	140	307	24	142	370	17	140	436
MB	31	153	336	26	155	406	18	152	478
ON	49	245	542	37	224	596	24	204	650
QC	57	288	641	43	264	705	29	239	770
NB	51	257	570	38	235	628	25	213	686
NS	68	342	760	51	313	837	34	284	914
PE	68	341	758	51	312	835	34	283	911
NF	2	8	18	1	7	19	1	7	21
N2O Reduction (g N2O-N/ha y)									
Prairies	27	132	289	22	133	349	16	132	411
Rest of Canada	45	225	499	34	206	550	22	187	600
N2O Reduction (kg CO2e/ha y)									
Prairies	13	62	135	10	62	163	7	62	192
Rest of Canada	21	105	234	16	96	257	10	87	281

Winter Wheat Assumptions

Reduction in N_2O emissions were calculated by soil landscape polygon and averaged by province.

BAU N Fertilizer use:
2025 1.1 x 2017 Prairies, Rest of Canada constant at 2017 rates
2030 1.19 x 2017 Prairies, Rest of Canada constant at 2017 rates

Reduction in N fertilizer use as part of 4R implementation: Basic 0%; Intermediate 10%; Advanced 20%

2017 No 4R 20%; Basic 20%; Intermediate 20%; Advanced 20%
2025: No 4R 20%; Basic 15%; Intermediate 15%; Advanced 40%
2030: No 4R 20%; Basic 10%; Intermediate 10%; Advanced 60%

4R Implementation

Basic (N_2O Reduction modifier = 0.85)

Source:	Ammonium based formulation with guaranteed analysis.
Rate:	Apply N based on nitrogen balance or OMAFRA guidelines. Set field specific N rates for winter wheat considering field specific yield history and soil types in relation to yield potential of other fields on farm and in region. Consider probabilities for weather variations when setting rates.
Time:	Apply required N as soon as practical in spring. No N application on frozen soil and/or snow-covered ground. Note: N from NP sources (MAP, DAP APP) allowed for fall at P rate.
Place:	Surface apply in spring.

Intermediate (N_2O Reduction modifier = 0.75)

Source:	Same as Basic, plus use enhanced efficiency fertilizers (nitrification inhibitors (NI), double inhibitors (NI and Urease inhibitors (UI)) or controlled release (CR)) make up at least 33% of total N total N application, targeted to high moisture, high risk situations.
Rate:	Same as Basic. Set zone rather than field N rates, based on estimates of residual N + mineralization
Time:	Same as Basic
Place:	Same as Basic

Advanced (N_2O Reduction modifier = 0.65)
Source: Same as Intermediate, plus enhanced efficiency fertilizers make up at least 50% of total N application, targeted to high moisture, high risk situations.
Rate: Same as Intermediate, plus variable rate based on digitized zone maps.
Time: Same as Intermediate, plus split application in season (at most 1/3 of N as sidedress)
Place: Same as Basic, plus apply in subsurface bands/injection using specialized equipment

Winter Wheat (Cumulative reductions)

	2017			2025			2030		
	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	23	117	215	18	107	263	12	98	310
AB	505	2489	4503	417	2516	6043	300	2482	7717
SK	996	4913	8891	822	4966	11933	593	4899	15239
MB	1472	7289	13265	1214	7363	17808	876	7256	22744
ON	11616	58157	107171	8712	53298	130866	5808	48439	154561
QC	640	3218	5962	480	2947	7282	320	2675	8602
NB	16	82	151	12	75	185	8	68	218
NS	75	380	704	57	348	860	38	316	1016
PE	129	648	1202	97	594	1468	64	539	1735
NF	0	2	3	0	2	4	0	1	5
N2O Reduction (kg N2O-N)									
Prairies	2973	14691	26659	2452	14845	35785	1769	14637	45700
Rest of Canada	12501	62604	115408	9375	57370	140927	6250	52136	166446
N2O Reduction (kt CO2e)									
Prairies	1.4	6.9	12.5	1.1	7.0	16.8	0.8	6.9	21.4
Rest of Canada	5.9	29.3	54.0	4.4	26.9	66.0	2.9	24.4	77.9
Fertilizer N Manufacture (kt CO2e)									
All Canada	0.0	3.4	6.9	0.0	2.7	14.2	0.0	1.8	21.8

Winter Wheat (Cumulative reductions as a result of reduced N fertilizer Manufacture)

	2017			2025			2030		
N Fertilizer Manufacture (kT CO2e)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
AB	0.0	0.3	0.6	0.0	0.2	1.2	0.0	0.1	1.7
SK	0.0	0.5	1.0	0.0	0.3	2.0	0.0	0.2	3.0
MB	0.0	0.5	1.0	0.0	0.4	2.1	0.0	0.2	3.1
ON	0.0	2.2	4.4	0.0	1.6	8.7	0.0	1.1	13.1
QC	0.0	0.1	0.2	0.0	0.1	0.4	0.0	0.1	0.6
NB	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
PE	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1
NF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N Fertilizer Manufacture (kT CO2e)									
Prairies	0.0	1.2	2.6	0.0	0.9	5.2	0.0	0.6	7.9
Rest of Canada	0.0	2.3	4.7	0.0	1.7	9.3	0.0	1.2	14.0

Winter Wheat (per hectare reductions)

	2017			2025			2030		
N2O Reduction (g N2O-N/ha)	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced	Basic	Intermediate	Advanced
BC	9	46	85	7	43	104	5	39	123
AB	12	58	105	10	59	141	7	58	180
SK	11	54	97	9	54	131	6	54	167
MB	57	282	513	47	285	689	34	281	880
ON	31	157	289	24	144	353	16	131	417
QC	42	209	387	31	191	473	21	174	558
NB	61	305	565	45	279	690	30	253	815
NS	29	147	272	22	134	332	15	122	392
PE	36	182	338	27	167	412	18	151	487
NF	16	79	146	12	72	178	8	65	211
N2O Reduction (g N2O-N/ha y)									
Prairies	27	131	239	22	133	320	16	131	409
Rest of Canada	32	161	297	24	147	363	16	134	429
N2O Reduction (kg CO2e/ha y)									
Prairies	12	61	112	10	62	150	7	61	192
Rest of Canada	15	75	139	11	69	170	7	63	201