The Economics of 4R BMP Implementation and Emissions Reductions from Fertilizer

An Industry Perspective on Financial Implications of the 30% Nitrous Oxide Emission Reduction Target

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Sponsored in Partnership by Fertilizer Canada and Canola Council

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Authors' Note

Fertilizer nitrogen management is incredibly complex and in the final analysis site specific. Crop producers and their advisors must synthesize knowledge derived from science and experience and integrate economics, logistics, and agronomics to manage crops within a highly variable growing environment. Each farm and in fact each field offers a unique set of challenges that change from one year to the next. 4R Nutrient Stewardship provides an integrated approach to nutrient management in cropping systems. The 4R approach is based on scientific principles, but relies on local knowledge derived from research, demonstration, and experience to adapt and develop appropriate BMPs at the farm level. Fertilizer Canada along with partners like the Canola Council have championed the adoption of 4R BMPs within a Climate Smart approach to sustainable intensification for over 15 years.

This study, as in any study that attempts to forecast a future state, required us to make assumptions on future trends in crop prices, fertilizer prices, inflation rates etc. Given the disruption of global supply chains due to Covid 19 and more recently the war in Ukraine, assumptions were made within a highly volatile environment. When developing economic trends out to 2030, we assumed a gradual return to more normal market conditions for crop and fertilizer prices and a decline in the overall inflation rate to the pre-Covid range. Time will tell if this holds true or if the current disruption is the new normal.

This paper is written primarily for the industry to stimulate discussion and is not presented in a scientific peer review journal or scientific monograph style. We have kept references in the main text to a minimum but will include some key scientific references on the effectiveness of BMPs in on-line supplemental material. Modelling produces voluminous data sets and we have also moved some of the detailed financial and analytical data at the regional level to appendices.

Canadian crop farmers have over the past three decades steadily increased total production, maintained the financial viability of the Canadian farm, and still made considerable progress in reducing the carbon footprint of Canadian crops. Recent work from Saskatchewan suggests that on Prairie farms crop production may be approaching net zero and from 2005, the baseline for Canada's Paris commitment, to 2016, sectoral emissions dropped 53%, more than is required to meet the 2030 Paris target.[1] Adoption of reduced tillage systems and improved nitrogen management have been the two major drivers reducing the carbon footprint of Canadian crops. Adoption of climate smart practices is not just a western phenomenon, farmers in Ontario are highly invested in split application of nitrogen fertilizer with available data suggesting it is practiced by a third or more of corn growers in the province. Inexplicably, neither net reductions from carbon sequestration nor 4R BMP adoption are captured and credited to crop production in the current version of the National Inventory Report.

One thing that has become increasingly apparent through the Covid and Ukraine crisis is that the global food supply and food security is fragile. World populations continue to grow and with it not only demand for more food but higher quality and healthier food. Canada is a major exporter of food as is Ukraine, and recent events have shown consequences of supply side disruption. Climate change is a serious issue that will have a significant impact on food security for many countries. While agriculture must do its part in limiting the impacts of climate change, emission reduction strategies that imperil the growth of world food supply and the financial futures of farmers and their families are simply not tenable.

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[1] *Awada L, Nagy C, Phillips PWB (2021) Contribution of land use practices to GHGs in the Canadian Prairies crop sector. PLoS ONE 16(12): e0260946.* https://doi.org/10.1371/journal.pone.0260946

Executive Summary

The Government of Canada has targeted a 30% reduction in on-farm nitrous oxide emissions from synthetic nitrogen (N) fertilizer by 2030. Using estimates from the 2022 National Inventory Report (NIR), total nitrous oxide emissions from fertilizer N reached 11.8 $MtCO_2e$ per year in 2020 setting the emission target at 8.3 $MtCO_2e$ per year in 2030. A reduction of 3.5 $MtCO_2e$ compared to the 2020 baseline.

One key component to reaching any emission reduction target is the implementation of 4R Nutrient Stewardship Best Management Practices (BMPs) on farm. To date there are approximately six million verified 4R acres under the Designation and Certification programs in Canada.

In this study, we use a series of regional scenarios for major Canadian cropping systems to build out a path forward to 2030 based on broader implementation of 4R Nutrient Stewardship BMPs and examine the financial implications and feasibility of the reaching the 30% target. To this end, we developed integrated economic and nitrous oxide emission models for major cropping systems in five regions and compared the effects of increased 4R BMP adoption rates on the regional crop production economy and nitrous oxide emissions from fertilizer. The GHG modelling used the N rate driven 2022 NIR methodology with modifications derived from the 4R Climate Smart Protocol to account for the influence of source, time, and place in reducing N_2O emissions. The BMPs included in the model were selected based on broad applicability across N fertilized crops and sufficient information available to estimate implementation costs.

There were three scenarios explored in this study:

1. A no yield increase scenario was initially compared to a yield increase scenario using reasonable if somewhat optimistic increases in BMP adoption out to 2030.
2. The second scenario looked at a yield increase that included a moderate increase in N fertilizer rate to support the additional yield. While substantial emission reductions were achieved, the 30% target was not reached in either scenario. Yield increase trends have been the norm in Canadian crop production and are necessary for farmers to maintain their financial viability.
3. A third scenario was developed, using the yield increase scenario values as the starting point, to estimate the levels of BMP adoption required to meet the emissions reduction target against the background of increasing crop yield. In this third scenario, 4R BMP adoption rates were increased iteratively until 30% reduction was achieved in each region.

Summary of Key Outcomes and Trends

The following observations and results are constrained by the assumptions used in the economic and emission estimating models used in this study.[2]

- The study encompasses Ontario, Quebec, and the Prairies with the Prairies broken into three regions based on soil zone, climate, and cropping system difference.
- The regions modeled represent over 90% of fertilizer N applications to crops inventoried in the 2022 NIR and over 90% of baseline 2020 nitrous oxide emissions attributable to fertilizer N.
- 4R BMP adoption rates in the 2020 baseline ranged between 5-25% depending on the BMP, the crop, and the region. These were progressively increased depending on the BMP, the crop, and

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[2] A full explanation of the assumptions and the modelling approach are available in the full report.

the 2020 baseline adoption rate reaching 2 to 8 times higher by 2030 in the no yield and yield increase scenarios.

- As reported in the 2022 National Inventory Report (2022 NIR), emissions from fertilizer N in the 2020 base year occur largely on annual crop land (96%) with only 4% attributable to fertilizer use on perennial crops.

No Yield Increase Scenario

- At the adoption rates used in the no yield increase scenario, the cumulative total cost of BMP implementation reached $3,420 million in 2030 and resulted in a cumulative reduction of 14.4 $MtCO_2e$ or $237/$tCO_2e$ reduced.
- Substantial annual reductions in nitrous oxide emissions from fertilizer were achieved reaching 2.50 $MtCO_2e$ per year by 2030 at a gross cost of $495 million per year and a net cost of $357 million over the 2020 baseline cost.
- Costs of BMP adoption were offset in part by savings in fertilizer costs based on the reductions in nitrogen rates linked to the various BMPs. When yield was kept constant net annual costs to crop growers were still a substantial $109 million or $43.68/$tCO_2e$ reduced.
- Costs per tCO_2e reduced were lowest in the high emission intensity corn-soybean-winter wheat systems in Ontario and Quebec and highest in the lower emission intensity canola-cereal-pulse systems in the Wet Prairie West Region of Alberta and Saskatchewan.
- Fertilizer emission reductions were accompanied by significant downward pressure on profitability in the no yield scenario. While this trend was driven in large part by the declining crop prices and increasing costs built into the model scenarios, the cost of BMP adoption was also a significant factor. Most regions experienced a negative net income by 2030 with contribution declines ranging from 34% to 47% from the peak of the 2022 year.
- The cost of BMPs at a farm level would be different than the averages of the region analysis shown above. The implementation of the full set of BMPs at farm level would cost approximately $34 per acre to implement in 2022 and rise to $43 per acre in 2030. This would represent between 7% and 10% of operating costs and would be a significant cost especially in the face of declining profitability unless further offsetting reductions in fertilizer and seed costs could be found without affecting yield.

Yield Increase Scenario

- In all regions the estimated contribution margins in 2030 increased with increasing yield ranging from $48 to $83 per acre higher than the no yield increase scenario. This represents a total $4.3 billion per year increase in contribution margin for the combined regions in the 2030 year over the no yield increase scenario. This represents a substantial increase in revenue for farmers and highlights the financial benefit of the longstanding trend of increasing yields.
- With increased yield, emission reductions in 2030 reached 1.6 $MtCO_2e$ with cumulative reduction of 10.4 $MtCO_2e$. These reductions, while still considerable are respectively 36 and 28% than those estimated in the no yield scenario.
- The yield increase scenario substantially slowed the erosion in contribution margin and supported farm profitability. For example,
    - Increasing corn and winter wheat yields in Ontario increased contribution margins by **$57 per acre or 23%.** This represents an additional **$351 million** of revenue in 2030 for Ontario producers.

  - For corn the impact of increased yield was substantial as the contribution margin increased $144 per acre or 118% in 2030 as compared to no yield increase. This equals **$305 million** of additional revenue on the total acreage of corn in Ontario for the 2030 year.
  - Increased canola and cereal yield in the Wet Prairie West region increased the contribution margin by **$85 per acre or 105%** in 2030 as compared to no yield increase. This equates to **$2.2 billion** of additional revenue on the total acreage of canola and cereals in the Wet Prairie West region for the 2030 year.
  - For canola the impact on increased yield increased the contribution margin by **$160 per acre or 118%** in 2030 compared to the no yield increase scenario. This equals **$1.7 billion** of increased revenue on the total acreage of canola grown in the Wet Prairie West region.
- Since BMP adoption rates and net BMP costs were near constant in both the yield and no yield increase scenarios but the tonnes reduced was substantially lower in the latter, the average cost per tCO_2e reduced increased by approximately 1.57-fold. The change in costs per tCO_2e reduced were substantially higher in Ontario (18-fold increase) than they were in Quebec and the Prairie Regions where increases ranged from two to four times higher.

Yield Increase and Adoption Rates Required to reach Reduction Targets

- Following the above, and assuming that growers would not be interested in reduction strategies that eroded their margins, adoption rates were increased for the yield increase scenario until the 30% emission reduction was achieved. Results varied by region but reaching the 30% reduction essentially required adoption of multiple advanced 4R BMPs on nearly every acre of N fertilized crop.
- In Ontario and Quebec adoption rates of 100% would need to be achieved by 2030 to meet the 30% reduction. In the western regions adoption rates of between 60% and 70% would need to be achieved. It should be noted that the baseline 2020 adoption rates in Ontario and Quebec were higher than the western regions, meaning that the magnitude of the change needed in the western regions are as significant as in the eastern regions.

One caveat should be noted here. The model used the average of the 2020-2022 fertilizer price across all years, which by historical standards is high. If fertilizer price was to fall below this price or growers were less aggressive in reducing N rates, the cost savings from the fertilizer reduction would decrease, the net cost of BMP implementation would increase from those shown above, and the cost per tCO_2e reduced would also increase substantially. The underlying assumption in the model is that BMP adoption will increase Nitrogen Use Efficiency (NUE) and allow N rate reductions. There is a finite limit on NUE and stacking BMPs may not allow for linear rate reductions without yield loss.

Key Findings and Conclusions

- The challenge of reducing emissions from fertilizers to 30% below 2020 levels by 2030 is immense. There are very few growing seasons between now and then and reaching 30% is not realistically achievable without imposing significant costs on Canada's crop producers and potentially damaging the financial health of Canada's crop production sector.

- Canada will have to balance the goal of reducing greenhouse gas emissions from fertilizer application against farm profitability, economic growth and global food security. There is no free lunch in food production.
- This study shows that Canada can balance both its economic and environmental goals. With an increased yield, GHG emissions can be reduced by 14% by 2030 - a cumulative reduction of 10.4 $MtCO_2e$.
- Adoption of 4R N management practices can substantially reduce fertilizer N_2O emissions but it will take very close to 100% adoption of advanced practices on N fertilized crops to reach the 30% reduction target by 2030.
- To maintain net income, the cost of BMP adoption must be offset by savings in operational costs such as reduced fertilizer use or increased revenue from higher crop prices and/or increased yield. The results of this study suggest that cost savings alone cannot compensate for BMP implementation and increased crop revenue and/or external incentives will be required to cover the costs of practice change.
- Without increasing yield and revenue, the cost of implementing emission reduction strategies would in combination with inflationary pressures undercut the profitability of Canadian crop production.
- There will likely be little interested from growers in emission reduction strategies that risk the economic sustainability of their farms.
- Despite these trade-offs, Canada's farmers can use 4R Nutrient Stewardship principles to effectively reduce their carbon footprint.
- Environment and Climate Change Canada must integrate 4R Nutrient Stewardship into the National Inventory Report to ensure that progress towards a target can be monitored appropriately.
- The government appears committed to using international protocol with the NIR which follows the UN Intergovernmental Panel on Climate Change's standards for estimating and reporting emissions. This does not take into consideration improvements in farm-level nitrogen management creating an inaccurate picture of emissions from fertilizer.
- Progress in measuring, verifying, and reporting (MVR) against reduction goals is limited by the availability of high resolution and accurate farm activity data. Government needs to substantially increase investment in this area and develop systems that accurately capture on-farm data.
- Increasing intensity of crop production to meet growing domestic and international demand will limit the amount of reductions that can be achieved and increase the cost per tonne of reductions.
- The results of this study suggest that there is potential for significant downward pressure on contribution margin and net farm incomes, if crop prices decline and yields are not increased.
- Large regional differences were estimated in the cost per tonne ($\$/tCO_2e$) of emission reductions. Per unit costs were significantly lower in Ontario than in the semi-arid prairies.

- Government goals and the policies and programs that support those goals should be refocused on a comprehensive cropping system approach to carbon accounting and emission reduction aimed at sustainable intensification and reducing the carbon intensity of Canadian crops.
- Climate change is a serious issue. Government, industry, and farmers need to work together to continue to adopt climate smart agriculture practices and targets that reflect the realities of Canadian agriculture. This requires a comprehensive approach to managing GHG sources and sinks on the farm rather than focus on a single emission source.

This study focused on adoption of 4R BMPs with broad applicability and reasonably well-known costs. We used reasonable N rate reductions with the BMPs to simulate improved nitrogen use efficiency, and moderately aggressive reduction modifiers to simulate the emission reduction effects of source, time, and place. We did not model all possible BMPs and using different BMP combinations and different assumptions concerning crop prices, fertilizer prices, operational costs, and fixed costs would undoubtedly result in somewhat different numbers. However, in our opinion they would not significantly alter the trends or change the conclusions reported here.

Introduction

The Government of Canada announced their industry reduction targets for greenhouse gas emissions (GHG) in late 2020. These targets included a 30% absolute reduction in the greenhouse gas nitrous oxide (N_2O) arising from field applications of synthetic nitrogen fertilizer by 2030 using 2020 emissions as the baseline.

In the discussion paper released in April 2022, Agriculture and Agri-Food Canada (AAFC) states, *"the target is established relative to absolute emissions rather than emissions intensity."*

It further states,

"the objective of the national target for fertilizers is to reduce emissions, and that the primary method to achieve this is not to establish a mandatory reduction in fertilizer use that isn't linked to improved efficiency and maintaining or improving yields. Rather, the goal is to maximize efficiency, optimize fertilizer use, encourage innovation, and to work collaboratively with the agriculture sector, partners and stakeholders in identifying opportunities that will allow us to successfully reach this target."

The purpose of this paper is to provide crop producers, commodity organizations, advocacy groups, and policy makers with a non-governmental perspective on the reduction target, whether it is achievable by 2030, and at what cost. To this latter end, we have developed a detailed economic model that can be used to calculate total and incremental costs for a specific farm or regionally using the major crops in the region. We have coupled this model to a GHG calculator that allows estimation of the N_2O emissions and reductions that may be achieved through practice change. The GHG calculator is derived from the 4R Climate Smart Protocol (4R CSP). This protocol is derived from the National Inventory Report (NIR) methodology with updates to include the methodology revisions in the 2022 NIR.[3]

These tools were applied regionally using five different BMPs in five regions of the country. For each region, a no yield increase was compared to a yield increase scenario using incrementally increased adoption rates out to 2030. A third set of scenarios used the increased yields and then iteratively increased the adoption rates until the 30% emission reduction was achieved.

This paper will comment on a number of issues with the NIR as well as benefits and barriers to the various BMPs proposed in the AAFC discussion paper as well as provide some first approximations of the economic implications of a 30% reduction.

Background

Nitrous Oxide Emissions from Fertilizer

Very little of the N fertilizer applied to Canadian crops is emitted as N_2O. However, N_2O is a long-lived greenhouse gas with a 100-year global warming potential (GWP) 298 times greater than carbon dioxide. The release of 1 kg N_2O from fertilizer has an equivalent effect on climate forcing of 298 kg of carbon dioxide or the same effect as running 110 L of diesel through the farm tractor.

Once fertilizer N is added to cropping systems, several transforming processes within the N cycle produce N_2O (Figure 1). Direct nitrous oxide emissions from fertilizer are those resulting from processes in the soil primarily nitrification and denitrification. Indirect emissions arise from N lost from the system through volatilization of ammonia and leaching/runoff of nitrate. Nitrogen lost through these mechanisms can be redeposited outside the cropping system and a portion converted to nitrous oxide in the receiving environments. Direct emissions are typically 3 to 5 times higher than indirect emissions

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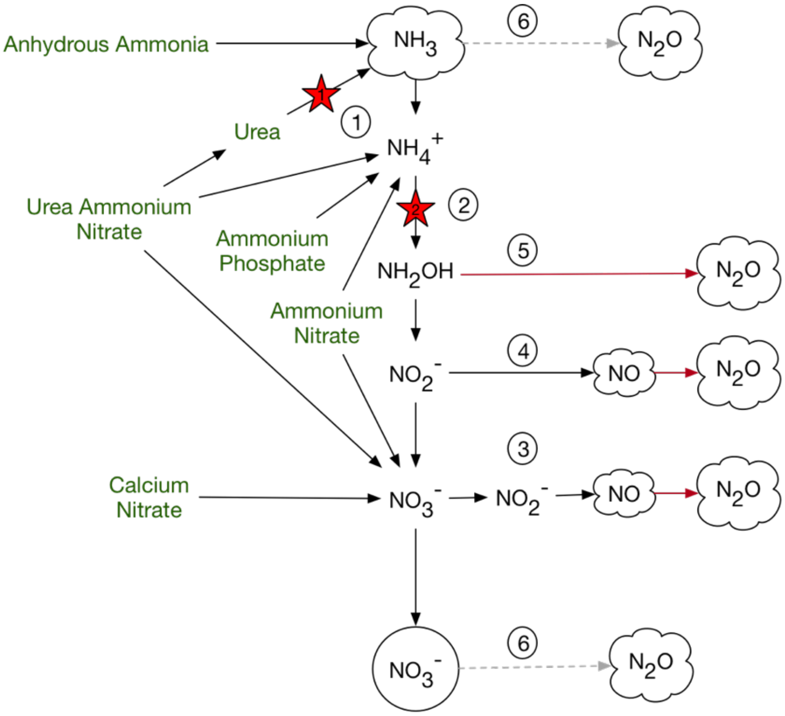
[3] Canada 2022 National Inventory Report is available at https://unfccc.int/documents/461919

depending on climatic and soil factors. Within the indirect emissions those attributable to leaching/runoff tend to be 2-3 times higher than those attributable to volatilization loss.

Figure 1. Processes Involved in N_2O Emissions from Fertilizer N.



Pathways from fertilizer products (in green) to microbial N_2O *production in soil. 1) Urea hydrolysis, 2) nitrification, 3) denitrification, 4) nitrifier denitrification, 5) nitrifier nitrification, 6) in direct* N_2O *emissions associated with* NH_3 *and* NO_3 *– loss to the environment. The red stars indicate process inhibited by 1) urease inhibitors and 2) nitrification inhibitors.*

Source: D. Burton (2018) *A Review of the Recent Scientific Literature Documenting the Impact of 4R Management on* N_2O *Emissions Relevant to a Canadian Context.* https://fertilizercanada.ca/resources/

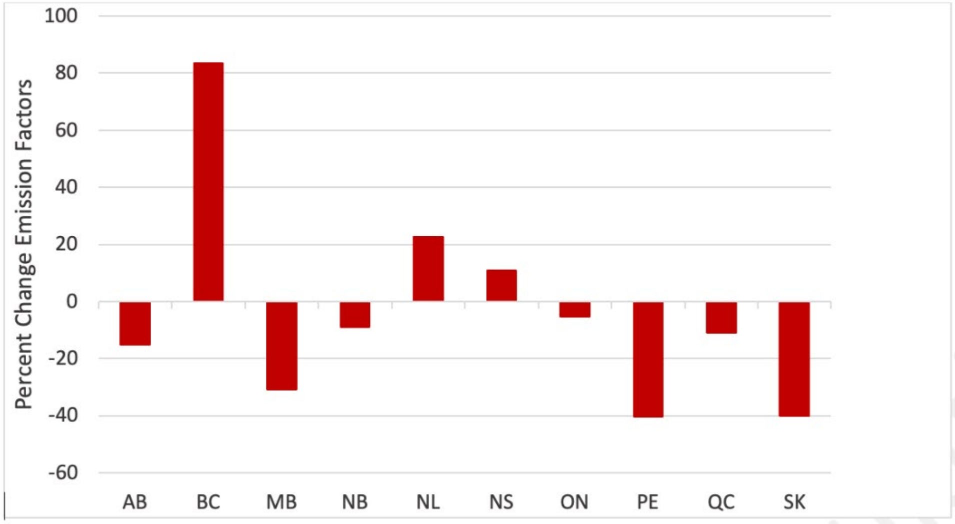
Measuring Nitrous Oxide Emissions from Fertilizer

Nitrous oxide emissions from soil are highly variable in time and space. Measuring emissions from agricultural soils is technically complex and requires sophisticated equipment and scientific expertise. Actual measurement is not currently feasible outside of a research framework. At farm and field scale, emissions are estimated using regionalized equations and/or process-based models. These estimation techniques are not particularly accurate when applied to a single field in a single year, but the accuracy improves when run over thousands of fields for multiple years.

One of the issues that needs to be clarified is what tool will be used to measure progress in N_2O reductions. The current tool used by Environment and Climate Change Canada (ECCC) to set the absolute emission reduction target is the NIR. The NIR is updated annually but there is a two-year lag so the 2022 NIR released by ECCC in April 2022 covers the 2020 baseline year. In International Panel on Climate Change (IPCC) parlance, Canada's NIR is a blended Tier 1 and 2 approach. It uses a regionalized country specific approach based on ecodistricts for estimating direct emissions (Tier 2) and a blend of IPCC defaults and regionalized variables for the indirect emissions. The methodology for estimating N_2O

emissions from agricultural soils was updated in the 2022 NIR[4]. The most significant changes were in the emission factors used at the ecodistrict level to calculate direct emissions and how the emission factors were modified to lower emissions from crop residues, manure N applications, and perennial crops. Compared to the previous methodology the change in emission factors resulted in lower emissions in drier regions and higher emissions in wetter regions (Figure 2).

Figure 2. Relative Changes in Ecodistrict Emissions Factors with Implementation of New Method.



This methodological update results in lower emissions from fertilizer N than previously estimated and sets the baseline 2020 emissions from fertilizer at approximately 11.8 MtCO$_2$e/y and the 30% reduction at 3.5 MtCO$_2$e/y.[5] Broken out by province emissions attributable to fertilizer are still highest in Saskatchewan and lowest in Newfoundland. It is also notable, that more than 95% of N$_2$O emissions arise from fertilizer applications to annual crops (Figure 3).

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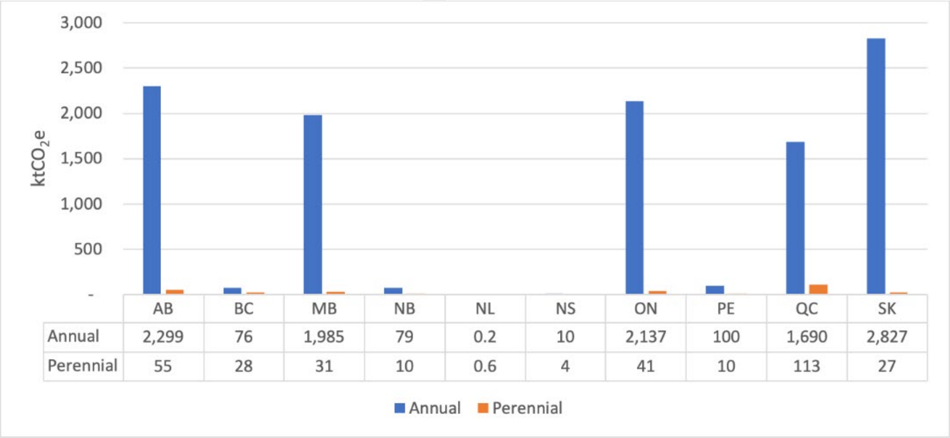
4 The new methodology is largely based on *Liang et al. Nutr Cycl Agroecosyst (2020) 117:145–167* https://doi.org/10.1007/s10705-020-10058-w(0123456789().,-volV()0123456789().,-volV

[5] This paper reports, except were otherwise noted, on nitrous oxide (N$_2$O) emissions. Emission results are reported regardless of greenhouse gas type in CO$_2$e units, the common unit of GHG reporting. Emissions of N$_2$O are converted to CO$_2$e by multiplying by 298 the 100 yr GWP for N$_2$O used in the 2022 NIR.

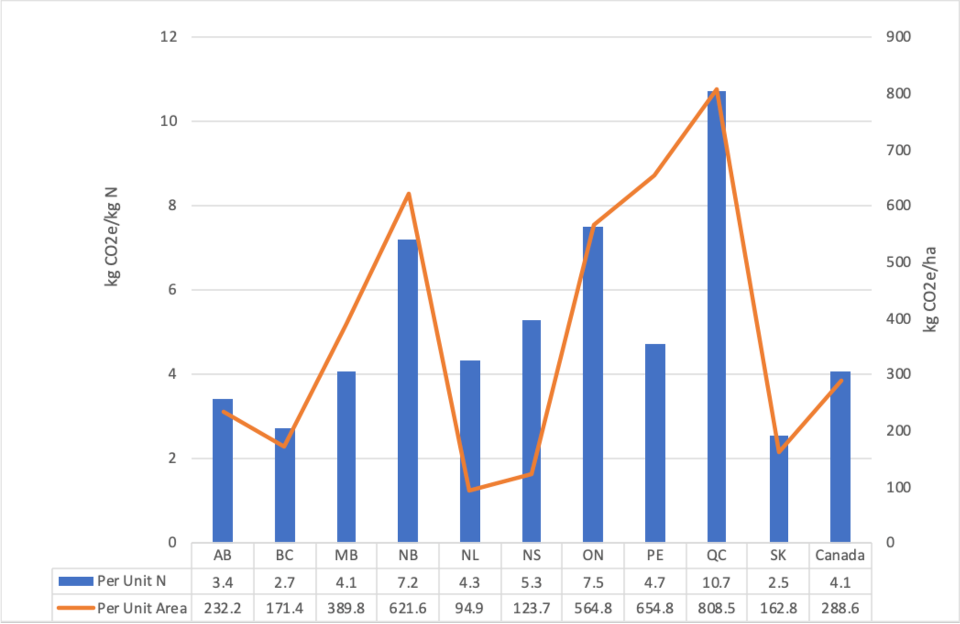
Figure 3. Provincial Nitrous Oxide Emission from Nitrogen Fertilizer by Crop Type.



	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK
Annual	2,299	76	1,985	79	0.2	10	2,137	100	1,690	2,827
Perennial	55	28	31	10	0.6	4	41	10	113	27

In contrast to absolute fertilizer emissions, Saskatchewan has the lower emission intensities primarily due to its semiarid climate and modest N rates (Figure 4). Emission intensity is an important consideration when deciding what BMPs will provide the best combination of N_2O reductions and economics in a region. For example, switching a kilogram of N from a conventional product to an enhanced efficiency fertilizer (EEF) will likely have 6-10 times greater impact on N_2O emission in Quebec compared to Saskatchewan and be 6-10 times more cost effective in dollars per tonne of CO_2e reduced.

Figure 4. Fertilizer Nitrous Oxide Emission Intensity by Province.



	AB	BC	MB	NB	NL	NS	ON	PE	QC	SK	Canada
Per Unit N	3.4	2.7	4.1	7.2	4.3	5.3	7.5	4.7	10.7	2.5	4.1
Per Unit Area	232.2	171.4	389.8	621.6	94.9	123.7	564.8	654.8	808.5	162.8	288.6

Use of the NIR in its current 2022 form to measure progress towards the 30% nitrous oxide reduction goal is problematic and these issues have significant implications going forward.

- The current NIR methodology for estimating N_2O is driven by total fertilizer N assigned to an ecodistrict. In essence, it is N rate driven and is not sensitive to 4R source, time and place BMPs.
- The NIR will need to be modified such that it is sensitive to 4R driven changes in N management or for the purposes of tracking progress an alternate measurement system will need to be deployed. ECCC is aware of this problem but has not made a firm commitment on doing the necessary work to implement an appropriate methodology for tracking progress.
- Tracking farm activity data that captures 4R BMP adoption as well as other land management and crop rotational changes will be crucial in providing accurate assessment of reductions. Currently data on nitrogen fertilizer practices are not sufficiently granular to capture regional adoption rates of the 4R BMPs and the emission reductions attributable to those BMPS.
- Ongoing changes to the NIR will result in a moving target. (For example, the IPCC has adopted 273 as the 100-Year GWP for nitrous oxide while the 2022 NIR used the older 298 value.) Some of these changes may require changes in reduction strategies.

The Government will need to commit significant resources to updating both the NIR methodology and improving the quality and granularity of data used in the estimates. As there are only eight growing seasons in which to implement practice change and measure impacts, updating the NIR should be an urgent priority for ECCC and needs to be undertaken with full transparency and consultation with the crop industry and non-government scientists.

Rate Reduction and Emission Reductions

Farmers and agronomists view N as the yield driver in non-leguminous crop production and are generally reluctant to reduce N rates for fear of yield loss. The consequences of a rate reduction strategy were explored in a 2021 study performed by MNP (Figure 5).[6] In their analysis, a straight-line reduction culminating in a 20% total reduction in N rate by 2020 would result in significant yield gaps and approximately $10.4 B in lost production for Canada's three major N fertilized crops. The MNP study was based on a worst-case scenario. What would the impact be if Canada decided to follow a strict N rate reduction strategy, similar to what was underway in the European Union. Keep in mind that the current version of the NIR is only sensitive to N rate and the MNP study was performed to point out that problem as well as to point out that a rate reduction strategy was untenable. Recent events in the Netherlands have illustrated the social consequences of limiting fertilizer N use to the extent that it impacts the economic sustainability of farms.

As will be discussed in a later section, we have used a combination of rate optimization and yield increases in exploring the impacts of different BMPs on financial sustainability. Loss of production is an unacceptable outcome both from an economic perspective but also from a GHG mitigation strategy. Global demand for food, fibre, and biofuels is rising and will continue to rise as global populations grow through the balance of the 21st century. Any production loss in Canada will be made up elsewhere on the planet resulting in more marginal land brought into production, loss of biodiversity, soil degradation, and replacement of Canadian production with cropping systems with potentially greater emission intensity than Canadian crops. Leakage of N fertilizer and the associated emissions to jurisdictions outside Canada can potentially undo the mitigation value of reduced N_2O emissions in Canada. If reductions in emissions are coupled with a decline in crop production leakage will certainly occur. Canadian farmers will carry the economic cost of N_2O reduction from fertilizer, but there will be little

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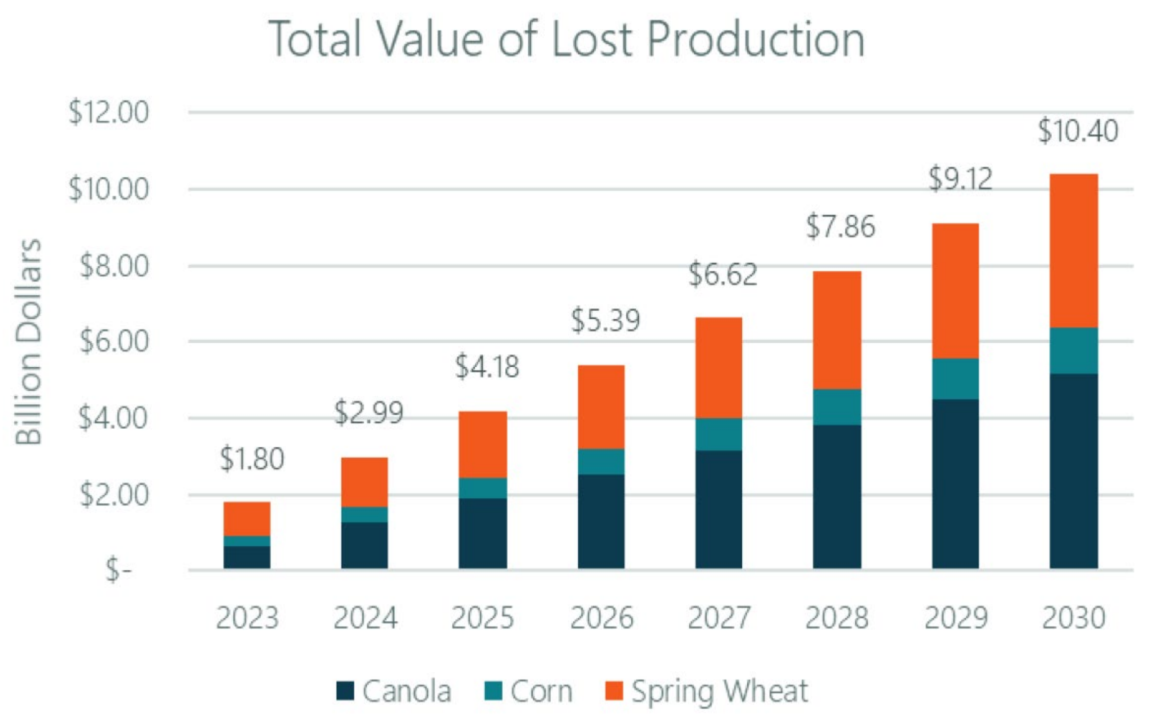
[6] Implications of a Total Emissions Reduction Target on Fertilizer: MNP Report https://fertilizercanada.ca/resources/implications-of-a-total-emissions-reduction-target-on-fertilizer-mnp-report/

impact globally as those emissions are transferred offshore. This is a totally foreseeable result that has not been considered in the AAFC Discussion Paper.[7]

The Government currently agrees with the industry position that a rate reduction strategy is untenable, and the way forward is through implementation of a 4R strategy that focuses on driving adoption of right source, time, and place BMPs combined with rate optimization. Rate reductions when they occur will be brought about through optimization strategies and improved nitrogen use efficiency. However, the climate goal of absolute reduction in N_2O emissions, may not be entirely compatible with the Government of Canada's export growth target of $75 billion worth of agriculture products by 2025.

Furthermore, improvements in crop genetics, crop protection, and soil health may require additional nutrients to ensure full yield potential is reached. This may create a situation where increased N use may reduce the carbon intensity (gCO2e/kg crop) of N fertilized crops but increase absolute emissions. The agricultural value chain is more interested in reducing emission intensity and carbon intensity scores on crop products than achieving absolute reductions in food and biofuel production.

Figure 5. Implications of a 30% Emissions Reduction Target on Fertilizer – Analysis of Potential Direct Financial Impacts on of a Fertilizer N Rate Reduction Based Strategy.



Move to Full and Fair Carbon Accounting in Crop Production

Under IPCC reporting standards N_2O emissions arising from N returned to the cropping system through crop residues must be accounted for in Canada's NIR. Emissions from residues are approximately one

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[7] Guarding against leakage is considered at a high level in ECCC's Environmental Plan *A Health Environment and a Healthy Economy* from the perspective of preventing large emitters relocating to avoid paying a price on carbon pollution and is not relevant to the issue of crop production and the fertilizer N required to support higher yields moving off shore.

half to one third of emissions from fertilizer. A 1% decrease in emissions from fertilizer accompanied by a 1% increase in yield will cut the net reduction in roughly half. It is worth noting that under IPCC rules, N_2O emissions from crop residues along with fertilizer are reported under agricultural soils, while carbon sequestered in soil is accounted for separately under the LULUCF section. [8]

Residues returned to the soil are the main feedstock for building soil carbon and improving soil health. Crop production carries the N_2O emission burden for residues but is not credited for the carbon sequestration. On the Canadian Prairies, adoption of direct seeding techniques and reduction in summerfallow have significantly reduced tillage operations and led to significant carbon sequestration. A recent Prairie study on the effects of changes in farm practices on GHGs from the cropping sector found that when carbon sequestered in agricultural soils is included net GHG emissions had dropped from 10.81Mt CO_2e in 1985 to 2.2 Mt CO_2e in 2016.[9] Cropping systems are both a source and sink of GHGs. Reducing fertilizer N emissions is only one aspect of lowering the carbon footprint of Canadian crops. A fairer and more productive approach would be focussed on the carbon footprint of crop production that included both the sinks and reduction/avoidances with an intensity target for the cropping system rather than absolute target focussed on only a single emissions source.

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[8] Land Use Land Use Change and Forestry

9 Awada L, Nagy C, Phillips PWB (2021) *Contribution of land use practices to GHGs in the Canadian Prairies crop sector*. PLoS ONE 16(12): e0260946. https://doi.org/10.1371/journal.pone.0260946

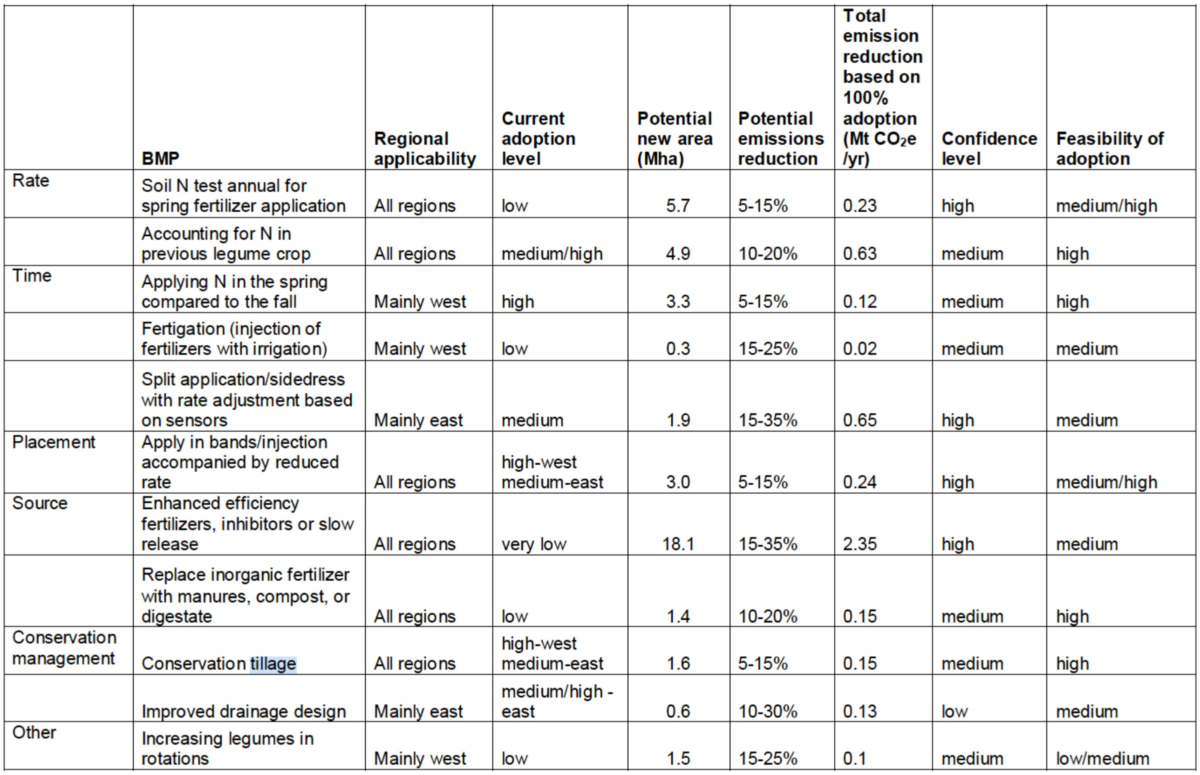
Role of BMPs in Reducing Nitrous Oxide Emissions from Fertilizer

The purpose of this section is to provide some background and commentary on the N_2O reducing potential of various BMPs within a 4R Nutrient Stewardship context. We will not provide a comprehensive review of the science behind the BMPs.[10] Our view is that the science behind the BMPs proposed by AAFC is sound and has been reviewed adequately by Canada's nitrous oxide scientists. Rather the purpose of this section is to provide a brief overview of the concepts behind the BMPs, why they are expected to reduce N_2O, as well as point to expected benefits from and barriers to implementation. Hopefully, this section will provide some food for thought for the cropping industry as well as policy makers as they move into implementation of an appropriate N_2O emission reduction strategy. We are also of the opinion that several potentially important BMPs have been excluded from the AAFC list in the discussion paper and policy instruments such as the OFCAF[11] program and we have included them in the following discussion.

Discussion Paper and OFCAF Supported BMP

The BMPs suggested in the AAFC Discussion Paper are for the most part those that are supported through the OFCAF program (Table 1).

Table 1. Best Management Practices from Annex B of the AAFC Discussion Paper.



	BMP	Regional applicability	Current adoption level	Potential new area (Mha)	Potential emissions reduction	Total emission reduction based on 100% adoption (Mt CO_2e /yr)	Confidence level	Feasibility of adoption
Rate	Soil N test annual for spring fertilizer application	All regions	low	5.7	5-15%	0.23	high	medium/high
	Accounting for N in previous legume crop	All regions	medium/high	4.9	10-20%	0.63	medium	high
Time	Applying N in the spring compared to the fall	Mainly west	high	3.3	5-15%	0.12	medium	high
	Fertigation (injection of fertilizers with irrigation)	Mainly west	low	0.3	15-25%	0.02	medium	medium
	Split application/sidedress with rate adjustment based on sensors	Mainly east	medium	1.9	15-35%	0.65	high	medium
Placement	Apply in bands/injection accompanied by reduced rate	All regions	high-west medium-east	3.0	5-15%	0.24	high	medium/high
Source	Enhanced efficiency fertilizers, inhibitors or slow release	All regions	very low	18.1	15-35%	2.35	high	medium
	Replace inorganic fertilizer with manures, compost, or digestate	All regions	low	1.4	10-20%	0.15	medium	high
Conservation management	Conservation tillage	All regions	high-west medium-east	1.6	5-15%	0.15	medium	high
	Improved drainage design	Mainly east	medium/high - east	0.6	10-30%	0.13	low	medium
Other	Increasing legumes in rotations	Mainly west	low	1.5	15-25%	0.1	medium	low/medium

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[10] A recent review of the relevant literature by Burton (2018) is available on the Fertilizer Canada Website.

[11] On-Fame Climate Action Fund

Annual Nitrogen Soil Testing – Right Rate BMP

The standard for determining soil test nitrogen (STN) is the nitrate-N test which measures the readily plant available nitrogen. Ammonium, the other plant available N form, tends not to accumulate in soil and is generally not included in STN. Soil testing for N can be performed at any time of year but time of sampling needs to be considered in the interpretation of results. Post-harvest fall testing after the soil has cooled is the standard approach used on the semi-arid prairies and there is generally reasonable correlation between fall and spring soil test nitrogen. Fall or spring testing is not a good predictor of available N for the growing season outside the prairies. In humid environments, where soils may be saturated and unfrozen through the winter, nitrate measured in the fall may be lost through denitrification and leaching. Sampling depth is also important; nitrate is mobile in soil and can accumulate in the lower reaches of the rooting zone. This N may not be available in the earlier part of the season but can be accessed as the roots extend downward. Deeper sampling is generally recommended for nitrogen (as compared to sampling for phosphorus and other nutrients) with separate 0-15 cm (0-6 in) and 15-60 cm (6-24 in) the most common configuration.

Fall soil testing for N in semi-arid regions indicates if there is residual available N in the soil following harvest and is useful in determining if the crop was over fertilized. It is less useful for this purpose in Eastern Canada since loss mechanisms can be active during the period before and after harvest. Spring soil testing, as close to seeding as possible, is the best time for using soil test N in developing rate recommendations in Western Canada. In-season, the pre-sidedress nitrogen test or PSNT can be useful in setting split fertilizer N application rates in corn.

AAFC suggests in their discussion paper that nitrogen soil testing can contribute to reduced nitrous oxide emissions from fertilizer by 5-15%. Soil nitrogen testing is supported as a 4R Right Rate BMP under the OFCAF program. The underlying assumption is that increased soil testing would lead growers that are currently over applying to reduce their rates to optimum levels. While some growers may be overapplying, there is no compelling evidence that there is currently significant over application of nitrogen to Western Canadian crops. In Eastern Canada, overapplication is limited to covering uncertainties in predicting year-specific crop N requirements. The AAFC discussion paper suggests that an additional 5.7 Mha/year or roughly 15% of arable crop land could be tested on an annual basis. This increase when combined with current annual soil test volumes would bring annually tested fields in the range of 45-55% of total fields.

Considerations

Soil testing for nitrogen has been widely available in Canada for over 50 years. Soil testing is largely performed by private laboratories and total test volumes are close to that reported in the industry's soil test summary.[12] Sample volumes have roughly doubled in the past two decades, from 165 thousand in 2001 to 325 thousand in 2020. Keep in mind that this system does not track N tests and the numbers above are for P tests. An N test is typically done on the Prairies as part of standard test package but not in the rest of Canada. Nitrogen test volumes are likely in the range of 125 to 175 thousand per year. Fertilizer Canada's Fertilizer Use Survey[13] suggests that there has been some increase in uptake over the past decade but less than a third of growers surveyed tested their fields for N on an annual basis.

- The available windows for sampling fields on the Prairies are after the soil cools in the fall and before freeze-up and after the soil thaws in the spring and before planting. Fall sampling can be delayed by late harvest and poor weather and is not useful for developing N recommendations

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[12] The Fertilizer Institute, Soil Test Summary, https://soiltest.tfi.org/

[13] 2020 Fertilizer Use Survey, Fertilizer Canada. https://fertilizercanada.ca/our-focus/stewardship/fertilizer-use-survey/

outside the Prairies. In much of Canada, the time between the spring thaw and optimal seeding date is typically less than a month leaving little time for sampling fields, analysis, and recommendation building. The pre-sidedress soil nitrate test requires sampling in June (a busy month for farmers), requires multiple samples per field (8-10 acres per sample), and requires rapid turnaround to inform the in-season application rate decision.

- While spring samples may be preferred for making recommendations, growers are typically looking for recommendations well ahead of planting. Recommendations using fall sample results are used for setting fall application rates and to pre-order or purchase fertilizer N for spring application to take advantage of lower fall prices.
- Sampling and analytical capacity would need to increase in-order-to provide rapid turn-around time on samples.
- New technologies capable of making in-field determinations may provide more immediate results and artificial intelligence approaches that predict the soil test values based on a multitude of variables are starting to be used to reduce the extent of actual sampling.
- Soil test N on its own is not a good predictor of yield response and is only one variable in more comprehensive N recommendation systems. These systems need data on a wider array of soil properties including soil organic matter and soil texture as well as tillage systems. More advanced systems also utilize past and forecasted weather and/or crop sensing information.
- There is currently no methodology for explicitly linking soil testing as a BMP to reductions in N_2O emissions from fertilizer, although most of its benefits could be assumed to be directly proportional to improvement in nitrogen use efficiency. The emission reduction is therefore per unit of crop produced, not per unit of fertilizer used, and not necessarily per unit area of cropland. The value will be in using soil testing as an indicator of residual N following harvest where high residual N would be an indicator of unused fertilizer N and over application. On the prairies, high residual N values are generally associated with low yields in drought years or manure applications.
- There are several logistical barriers to increasing soil testing in particular spring testing. There are several emerging analytical technologies that are shortening the turn-around time but the results from these novel methods need to be calibrated and understood before they are useful in optimizing fertilizer N rates.

Accounting for N in Previous Legume Crops – Right Rate

Crop residues from legumes tend to have higher N content and lower C:N ratios compared to cereals and oilseeds. Current thinking is that the lower C:N ratio results in higher net mineralization primarily due to reduced immobilization and potentially more available N for the crop that follows. The idea behind this BMP is that a cereal or oilseed following a legume requires less N fertilizer. There is also an assumption that the effects of legumes on N availability (the N credit) is not widely accounted for in N recommendations. Work on the Northern Great Plains has found that i) not all pulses produce N credits, ii) contributions of N to the subsequent crop are highly variable and generally in the range of 10-20 lb N/acre, iii) annual legumes are best treated as longer term rotational strategy.

Adding pulses to cereal and oilseed rotation on the prairies tends to have benefits such as disrupting cereal and canola disease cycles. However, pulse crops have their own set of diseases many that are shared among the different pulse crops as well as agronomic problems related to seeding and harvest.

Growers adding pulses to their rotation also need to consider changes to their weed control programs and increased erosion risk. Faba beans, peas and lentils will under normal conditions provide a N credit to the crop that follows while chickpeas and field beans typically do not. Growers in Western Canada often seed wheat on pulse stubble without a significant reduction in N rate and rely on the pulse credit to achieve high protein wheat.

Corn grown in corn-soybean rotations or following forage legumes tends to outperform continuous corn and in Ontario it is common to reduce fertilizer N rates 20-30 lb N/acre following soybean and by at least 100 lb N/acre following alfalfa. This doesn't seem to apply to corn or other crops following soybean in Manitoba where the net N benefit following soybean has been estimated at 6 lb N/acre.

Considerations

- In the 2020 crop year data used for the 2022 NIR, the area of annual legumes is 2 Mha for soybean and 3.7 Mha for pulses. There is an additional 3.3 Mha of alfalfa, but alfalfa is not turned over every year. The discussion paper suggests that accounting for N credits following legumes could reduce emissions on an additional 4.9 Mha and that adoption of this practice is already medium to high. The additional hectare estimate is in our opinion more in the range of 2-3 Mha as the practice is already well established.
- Updating and publishing regional estimates of N credits by legume crop and across a range of growing season conditions would assist agronomists in more realistically accounting for N credits and facilitate further adoption.
- Assigning a N credit is not a stand-alone issue and is tied to greater use of nitrogen soil testing and better techniques for predicting net mineralization rates as part of an integrated fertilizer recommendation system. Alberta's AFFIRM is an example of one such system. There needs to be a considerable research and development investment in developing the data required by expert recommendations systems for all the major cropping systems in Canada.
- Warm moist post-harvest conditions can result in rapid mineralization and the N credit showing up as soil test N results. This can lead to underapplication as the N credit essentially gets counted twice.

Applying N in Spring Compared to Fall – Right Time

Applying N fertilizer as close as possible to the time of maximum crop uptake can reduce risk of N loss and increase nitrogen use efficiency. Research on the prairies has shown that spring application tends to result in higher yields than fall application. This is particularly true when fall broadcast is used. Limited farm activity data makes it difficult to assess how much N goes down in fall on the prairies and pinpointing where it is a more common practice. Wet falls and/or early freeze-up, late harvests and high N prices tend to reduce fall-applied acres while the opposite conditions lead to increased fall N. In the 2019 Fertilizer Use Survey, canola growers reported that ≈20% of N is fall applied on the Prairies and the practice is more common (44% of respondents) in Manitoba.[14] Quarterly shipment data[15] suggests sufficient anhydrous ammonia is available for fall-application on 4-6 million acres and points to the practice being most common as a percent of total acres in Manitoba and least common in Alberta. However, the split between storage over winter at the dealer level and actual fall-application cannot be accurately assessed from shipment data. Farmers purchase granular N in fall, primarily urea, for spring application and store it on farm. Fall purchase allows farmers to take advantage of lower prices and to

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[14] 2019 Fertilizer Use Survey, Fertilizer Canada. https://fertilizercanada.ca/our-focus/stewardship/fertilizer-use-survey/

[15] Statistics Canada. Table 32-10-0038-01 Fertilizer shipments to Canadian agriculture and export markets, by product type and fertilizer year, cumulative data (x 1,000) **DOI:** https://doi.org/10.25318/3210003801-eng

pre-pay, which has taxation advantages, since farm financial accounting is often cash-based. These various disconnects between fall N sales and fall application, makes it difficult to assess how much urea or urea containing blends are fall applied or how much anhydrous is in storage at the dealer level.

In humid environments, for example Southern Ontario, where soils may not freeze and profiles are often fully recharged with moisture, overwinter N losses through leaching and denitrification can be substantial. Other than applications of ammoniated phosphorus sources, very little N fertilizer (less than 3% in corn and approximately 15% in winter wheat[16]) is fall-applied. The opportunity for conversion from fall to spring timing is therefore largely confined to the prairies. One of the advantages of fall application on the Prairies is reduced spring tillage and soil drying prior to seeding. Direct seeding has largely overcome the drying issue but fall-application may still be advantageous for growers in two pass systems.

While there is general agreement that switching from fall to spring, reduces N losses and fertilizer N emissions, research in Manitoba has shown that emissions can be lower from anhydrous ammonia applied in late fall compared to pre-plant in spring.

Considerations

- Fall application reduces spring workload and allows growers to seed more efficiently and closer to optimum planting dates. Switching from fall to spring may also involve a switch in placement from banding to broadcasting potentially reducing nitrogen use efficiency. The desired conversion is from fall application whether banded or broadcast to spring banding preferably in a direct seeding system which tends to result in higher NUE.
- Conversion from fall to spring N application may involve equipment changes particularly if the change to application is from fall to time of seeding. Growers may have to increase the capacity of their air drill and/or air cart to handle larger fertilizer volumes and rethink their fertilizer placement to avoid seedling damage.
- Fall-banding after the soil has cooled below 10°C is considered a 4R Climate Smart BMP on the Prairies. Moving to late fall-timing with a nitrification inhibitor may be a more achievable transition than conversion from fall to spring.
- Targeting conversion of fall to spring in regions with finer-textured soils on the moist Prairies will likely result in greater reductions per unit of N applied. Fine textured soils tend to saturate for extended periods in the spring triggering denitrification.

Fertigation (Injection of Fertilizers with Irrigation) – Right Time

Fertigation provides an opportunity to move N applications closer to time of maximum crop uptake and applying with irrigation water carries applied N into the rooting zone improving NUE. An advantage compared to other in-season surface application techniques. Fertigation works well with crops with a longer N uptake period such as potatoes. With cereals and oilseeds grown under irrigation the window for supplemental N can be quite narrow and depending on rainfall, irrigation may not be required. A large proportion of irrigated land (approximately 40%) grows legume-based hay or is annual silage grown on manured land and does not receive N fertilizer. The discussion paper suggests that the practice could be expanded to an additional 0.3 Mha, 40% of Canada's irrigated land base of 0.7 Mha. This may be optimistic in terms of area, but expansion of the practice should be encouraged particularly on high N using irrigated crops in both Eastern and Western Canada.

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[16] 2020 Fertilizer Use Survey, Fertilizer Canada. https://fertilizercanada.ca/our-focus/stewardship/fertilizer-use-survey/

Considerations

- Conversion to fertigation requires equipment that meters liquid fertilizer into the irrigation water stream. This will require investment as irrigation farmers will need to purchase injection equipment and potentially equipment for storing and hauling liquid N sources such as UAN.
- Irrigation timing and optimal fertilizer application timing may not coincide.
- Irrigation is applied on less than 2% of Canada's cropland. Even though the NIR methodology ascribes higher direct and indirect emissions to irrigated soils, converting half the irrigated acres to fertigation as suggested in the discussion paper would provide less than 1% of the required N_2O reduction.

Split Application/Sidedress with Rate Adjustment Based on Sensors – Right Rate/Right Time

Split-application offers advantages by allowing growers to adjust N rates based on growing season conditions. The practice is most feasible with row crops like corn where UAN can be side dressed through coulters or surface applied with Y-drops using a high clearance sprayer. Corn grower survey data from Ontario suggests that up to 40% of the total N applied to corn is applied in-season. Given that most growers applying in-season are also applying at or before seeding, the survey data suggests that the practice is already widely adopted in Ontario corn growing regions.

For cereal and oilseed crops, UAN or liquid urea can be applied using a high clearance sprayer fitted with streamer nozzles. Urea, ammonium nitrate, calcium nitrate and other granular products can also be broadcast. Surface applications are dependent on timely rain or irrigation to carry the N into the rooting zone and application of urea-based products can result in significant volatilization loss. Use of a urease inhibitor or a controlled release product can reduce volatilization losses but may also delay conversion to plant available forms.

The window for application tends to be quite narrow for cereals, no later than stem elongation for yield response, and optimal timing can be interrupted if poor weather makes fields untrafficable. Application of N closer to anthesis in wheat is used to increase protein content rather than yield but potentially increases N_2O emissions if the additional N is not fully taken up by the crop. Research on the prairies suggests that for cereals and oilseeds there is seldom a yield advantage to split-application compared to all N at seeding.

Equipment mounted sensors that adjust rates in real time across the field are one of several approaches that should be considered. Used in isolation they require a grower to commit to the split application/sidedress operation as the rates are not known in advance. Hand-held sensors, satellite imagery, and/or drone-based imagery can also be used to provide a pre-operational assessment of N status of a crop. Currently available sensing techniques do not directly sense N in the plant but detect indicators such as greenness or use normalized difference vegetative index calculations (NDVI) as a proxy for N status.

Mechanistic models can be used to predict N uptake and losses and provide growers insight into the N status of the crop and whether it needs to be supplemented as the season progresses. Artificial intelligence (AI) methods have been developed that predict N status based on a range of available weather and agronomic data. These new high-tech approaches are data intensive. A lower tech approach for corn is the Pre-side Dress Nitrate Test, basically an in-season soil test prior to making an application.

The techniques discussed above have one thing in common, they require some degreed of local or regional calibration or verification for each target crop.

Considerations

- Split-application is a 4R BMP and is effective in reducing N_2O emissions particularly for row crops in humid environments.
- There is already a relatively high level of adoption in Ontario. Opportunity for greater adoption of the practice is mainly on the Prairies.
- Split application may not lead to rate reductions when early season N losses are high. There is in fact a tendency for the final rates to be higher in years with greater rainfall, since more rain generally increases potential crop yield as well as potential N losses.
- For corn in Ontario, the yield advantage of split application is quite small on well drained loam soils. The costs of additional trips over the field need to be considered and may outweigh the yield benefits.
- As a risk management tool on the prairies, split application provides growers with an N saving option when stored soil moisture is low at seeding. Additional N can be applied if conditions improve. In normal moisture years, there is little or no yield advantage relative to all N at seeding.
- Equipment mounted sensors require considerable investment in hardware. Other techniques are available at lower cost that may allow growers to trial split applications with minimum investment in hardware.
- Split-application increases the complexity and timing of field operations.

Apply in Bands/Injection Accompanied by Reduced Rate – Right Rate/Right Place

Banding of granular or liquid fertilizers generally increases NUE compared to broadcasting. Banding reduces contact with soil and creates a fertilizer reaction zone that limits soil microbial activity. This slows nitrification and potentially reduces the nitrate available for denitrification and leaching should soil become saturated after fertilizer application. Placing N below the surface can also reduce volatilization provided bands are sufficiently deep, soil is sufficiently moist, and there is good closure over the band. Banding too shallow can reduce the benefits and lead to increased volatilization under dry condition and in coarser textured soils. Banding away from the seed, side-banding or midrow banding, avoids the seedling damage that can occur from placing N in the seedrow.

Yields tend to be 10-20% higher in prairie cropping systems where N is banded rather than broadcast. Just over 85-90% of N applied by canola growers on the Prairies is applied in bands and numbers are expected to be similar for cereals.[17] There is limited opportunity to increase banding on the Prairies. Farmers know that banding reduces N losses, increases NUE, and leads to higher yields; N is broadcast to save time. In Ontario, split application appears to be growing and surface banding (using Y-drops for example) may be reducing the volume of N applied through sub-surface banding in corn.

Considerations

- Although 85-90% of N fertilizer on the Prairies is banded, recent trends to broadcasting N on the Prairies are typically driven by time and equipment constraints.

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[17] 2021 Fertilizer Use Survey, Fertilizer Canada. https://fertilizercanada.ca/our-focus/stewardship/fertilizer-use-survey/

- Growers switching from broadcast to sub-surface banding will need to invest in banding equipment. This may require upgrading the seed cart to handle larger fertilizer volumes and/or a completely new or reconfigured air drill or seeder.
- The opportunity for conversion from broadcast to banding will likely coincide with growers need to turn over their seeding equipment.
- Opportunities for conversion from broadcasting to banding are likely highest in regions of Eastern Canada where broadcasting N is still common practice. However, in Eastern Canada broadcast/incorporated urea are considered equal in efficacy to banded urea, and general recommendations do not reduce rate for banding relative to broadcast/incorporated.

Enhanced Efficiency Fertilizers, Inhibitors, or Controlled Release – Right Source

Enhanced Efficiency Fertilizers (EEF) affect processes in the N cycle in ways that prevent N loss and increase NUE. Depending on the mode of operation they may also reduce N_2O emissions. Nitrogen stabilizers tend to disrupt N conversion processes and slow the transformations that lead to N loss and N_2O production. The most effective stabilizers for reducing N_2O are the nitrification inhibitors (NI). These products typically lower N_2O emissions by 25-49%. Urease inhibitors (UI) slow the conversion of urea to ammonium and reduce volatilization losses. They tend to be less effective at reducing nitrous oxide emissions, typically in the 5-15% range. There are NI products available for use with anhydrous ammonia, urea, and UAN and UI products for urea and UAN. Double inhibitor products containing both an NI and a UI are available for urea and UAN.

Different controlled release N products are available in the market, and the effectiveness of some products in reducing N_2O emissions has not been clearly established. Polymer coated urea (PCU), one of the more widely studied controlled release products, typically reduces N_2O by 10-28%. Keep in mind that these typical ranges reported vary widely depending on growing season conditions, application timing and other factors.

EEFs tend to increase NUE but may not increase yield. A yield response will only occur if crops are N limited and the EEF results in more N available to the crop compared to a conventional N product. Replacing conventional N with an EEF on a pound of N for pound of N basis will increase costs without an increase in revenue if the conventional product rate was sufficient. If N rates using conventional N products have been optimized, switching to an EEF should allow a modest reduction in rate without yield loss.

Consideration

1. EEFs particularly NIs are effective at reducing N_2O but may not work all the time. Reductions are estimates that are probable in aggregate over multiple fields and growing seasons.
2. EEFs can be applied like conventional sources, few logistic barriers to field application.
3. Cost and availability may be barriers to adoption that may not be completely offset by lower rates or higher yields. EEFs typically increase N fertilizer cost from 10-20% depending on product.
4. Current use of the EEF types above (effective in reducing N_2O emissions) is uncertain as sales volumes of the various products are proprietary business information. Farmer survey data estimates current EEF use at 10-15% of N fertilizer volume in the Prairie provinces, and 6-24% in Ontario. A significant increase in use will require expansion of manufacturing capabilities and output, and/or imports.

Replace Inorganic Fertilizer with Manures, Composts, or Digestate

The NIR methodology discounts direct emissions of manure N applied to annual crops by 16% per kilogram N applied compared to fertilizer N. However, the benefit of lower direct emissions is partially clawed back by higher volatilization losses resulting in indirect emissions. The 2022 NIR estimates total annual manure N production in Canada at 670 kt N. Of this 42% is directly deposited by animals on pastures, ranges, and paddocks and is largely unrecoverable for application to crop land. The remaining manure N (approximately 390 kt N) is applied predominantly to annual crops (290 kt N), perennial crops (68 kt N) and improved pasture (31 kt N). Application of manure N to annual and perennial crops is approximately 14% of applied fertilizer N. An additional quantity of N_2O emission, however, is also assigned to “manure management” and represents approximately double the N_2O emissions associated with manure application. These emissions represent N losses from livestock operations between excretion and land application.

The discussion paper lists replacement of synthetic fertilizer N with organic fertilizer N as an N_2O reduction BMP. Manure and other organic N sources may act as a slow-release fertilizer and as such may produce lower direct N_2O emissions per unit of N applied. Manure is the main source of organic fertilizer-N in Canada. Fields receiving manure in the Prairie Provinces are typically manured on a three-to-five-year cycle at rates significantly above the annual uptake rates of N and P for the receiving crops. Smaller operations in both Western and Eastern Canada with lower manure storage capacity may be applying more frequently.

Manure is not strictly an organic-N source; it contains readily plant available inorganic nitrogen most commonly as ammonium-N. The amount of readily plant available N varies with source, storage, and handling. None-the-less, a large proportion of the N contained in manure is tied to carbon in manure solids. This organic-N is released into the plant available N pool as manure breaks down over several cropping seasons. The mineralization of organic-N into available forms in the year of application ranges from 13-50% depending on manure source, time of application, application method, and environmental conditions.[18] As a fertilizer substitute manure is bulky, highly variable and release rates are hard to predict. Application timing in annual crops is largely confined to post-harvest before soils freeze or after the spring thaw and before planting. Winter application on frozen or snow-covered ground is not 4R Climate Smart BMP and is not permitted under manure management regulations in most provinces.[19] Composting manure prior to result in a more uniform and manageable product but substantial carbon as carbon dioxide and nitrogen as ammonia losses occur during the composting processes.

While the overall soil health benefits are undisputable, there are several GHG emission risks associated with manure use. Unlike synthetic fertilizer N, the organic-N in manure is not immediately available to the crop. To ensure adequate N supply, manure N is often applied at total N rates well in excess of the crop demand in the year of application. Manure mineralization is not confined to period of high N demand by the crop but proceeds whenever soil moisture and temperature conditions are conducive to soil biological activity and mineralization of manure carbon for energy. If mineralization rates exceed crop uptake over the growing season, this can lead to high residual nitrate levels in manured soils and increased risk of nitrogen loss and N_2O emissions.

While manure could be used more effectively recoverable manure volumes are too low to replace significant quantities of fertilizer N, more efficient application methods that reduce ammonia volatilization could make a small but significant reduction in N_2O emissions. For example, reducing

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[18] Nutrient Management Planning Guide. Alberta Agriculture and Food (2008). open.alberta.ca/publications/7086752#detailed

[19] Several provinces allow limited winter application for operations with limited storage volumes under grandfathering provisions or under emergency conditions.

estimated volatilization losses by half for manure applied to crops and improved pastures would reduce N_2O emissions by approximately 175 ktCO_2e or 5% of the total required reduction of 3,420 kt CO_2e. Technologies capturing the large volume of nitrogen lost from manure during storage and handling and converting it to forms suitable for land application could potentially displace fertilizer N and reduce N_2O emission from fertilizer but the net impact on N_2O would be relatively small.

Biosolid N is estimated at < 1% of all N applied to agricultural lands. Land application of biosolids from sewage treatment is regulated at the provincial level and typically requires immediate incorporation.

The discussion paper suggests that manure and other organics could replace inorganic fertilizer on 1.4 Mha. At average fertilizer rates (67 kg N/ha) this would require redirecting approximately 24% of the recoverable manure to new fields. This fertilizer replacement strategy may reduce N_2O emissions attributable to fertilizer by 4-6% but will have little impact on overall emissions from agricultural soils. The main benefits from improved manure management will be improved soil health and reduced phosphorus loading, reduction in N2O emissions will be a minor side-benefit.

Considerations

- The soil health benefits of appropriate manure use in cropping systems are well recognized.
- Fertilizer Canada in cooperation with the nutrient management community has developed BMPs for manure use within a 4R Climate Smart framework.
- Manure application is regulated at the provincial level with controls on rate, time, and place practices for field application.
- Efficient use of manure requires incorporation to prevent ammonia loss and solid manure application is currently incompatible with zero tillage systems.
- Nitrification inhibitors are available for use with liquid manures and have the potential to reduce N_2O emissions from land applied manure when combined with appropriate timing and placement practices.
- Increased hauling distances would be required to more widely distribute recoverable manure and will significantly increase manure application costs.
- Technologies to increase nutrient capture from recoverable manure during the stages from excretion to land application could have a substantial impact on emissions.
- Better methods for estimating N content and potential N mineralization rates would enable for more efficient use of manure.

Conservation Tillage

Conservation tillage typically slows turnover of soil organic carbon and leads to carbon sequestration as soils convert from a net carbon source to a net carbon sink. Conservation tillage also affects the soil moisture cycle and the nitrogen cycle and can result in an increase in N_2O emissions relative to conventional tillage. Conservation tillage prevents erosion, increases water holding capacity, and generally improves soil health. During transition from conventional to conservation tillage, higher fertilizer N rates may be required to maintain yield as N is immobilized with the sequestered carbon. As the conservation tillage system matures, nitrogen mineralization rates tend to increase. Direct seeding has been widely adopted on the Prairies and forms of reduced tillage such as strip till have become more common in the last decade in cropping systems and soil types where zero till systems are not operationally feasible.

Currently carbon sequestered in agricultural soils is reported under the Land Use Land Use Change and Forestry (LULUCF) section of the NIR following IPCC directives. Agriculture receives no credit for sequestered carbon in cropland but the N_2O from soil organic carbon turnover is part of the agricultural soil assertion in the NIR. The discussion paper suggests that conservation tillage could be expanded to an additional 1.6 Mha and may reduce emissions by 5-15% but do not specify if the reduction is net of carbon sequestered.

Considerations

- Rather than focussing on reductions from fertilizer, the focus should be on net in-field emissions from cropland with the aim of bringing them as close to net zero as possible. This would include the positive effects of carbon sequestration on reducing emissions and eventually could expand to other nature based and technical solutions on the farm such as biodiesel use in equipment, natural area preservation and/or restoration, and/or renewable electric sources.
- For the purposes above carbon sequestration should be calculated conservatively but not discounted for permanence as it is in offsetting protocols.
- Crop production should not be charged for the emissions from land use change such as urban expansion over which it has little or no control.

Improved Drainage

Installing tile drainage can reduce the length of time that the soil is saturated and reduce denitrification losses and direct emissions. More importantly drainage can allow growers earlier access to fields for spring operations. Nitrate-N can be lost in drainage waters and contribute to indirect emissions and eutrophication of surface waters. For example, tile drainage in watersheds feeding into the western basin of Lake Erie is a major source of N and P loading in the lake and declining water quality.[20] Drained water needs someplace to go and routing water from fields during spring runoff can increase downstream flow rates and contribute to flooding. Drainage is regulated by the provinces and rural municipalities may not want to accommodate drainage projects that impact their infrastructure such as road ditches, culverts etc.

Considerations

- Drainage of wetlands including ephemeral wetlands may disqualify growers from participation in various regulatory and voluntary carbon and/ecosystem service markets that have biodiversity criteria. For example, the Canadian Clean Fuel Standard contains biodiversity criteria that must be met.
- Some provinces have setbacks from drainage ditches or waterways that are constructed or used for carrying drainage waters. Application of manure, fertilizer or crop protection products may not be allowed in the set-back zones.
- New technology is making drainage easier to install and systems are emerging the store drainage water in spring and then recycle it as the crops water demand increases through the growing season.

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[20] Miller, S.A and S.W. Lyon. 2021. Tile Drainage Increases Total Runoff and Phosphorus Export During Wet Years in the Western Lake Erie Basin. Front. Water, 27 October 2021 Sec. Environmental Water Quality https://doi.org/10.3389/frwa.2021.757106

Increasing Legumes in Rotation

As discussed earlier, annual and perennial legumes that produce a net N benefit can reduce the fertilizer required for subsequent cereal and oilseed crops. These can include pulse crops (field peas, lentils, faba beans, chickpeas), oilseed legumes like soybean, and perennial forage crops like alfalfa and clovers.

A more important aspect of increasing legume acreage is the reduction or elimination of fertilizer N in the legume year(s) and the avoidance of fertilizer driven N_2O emissions. For example, going from a wheat, canola rotation to a wheat canola pulse may reduce N fertilizer use by up to a third. Switching from continuous corn to a corn soybean rotation could cut fertilizer N use and associated emissions in half. However, increasing low residue crops like soybean might reduce potential soil organic carbon storage and increase N_2O emissions from higher N crop residues compared to cereal or oilseed residues. Adding legumes to rotation helps break disease cycles and typically yields of non-legume crops are higher in rotations that include legumes.

There are several barriers to increasing grain legumes in rotations. While pulse crops break the disease cycle of cereals and oilseeds, they have diseases of their own several of which are shared among all the pulse species. Weed control options in pulses are limited and growers will need to rethink their herbicide rotations when adding pulses. Production costs can be high and yields low and specialized equipment such as land rollers and draper headers may be required for seeding and harvesting. Finally, market and/or market access can be an issue. On the Canadian Prairies lentil acreage expanded, largely at the expense of wheat acres, in the 2010's. Canada with greater than 60% of the export market is the largest global exporter of lentils. International and domestic demand, market access, agronomic and equipment issues place significant limits on expanding lentil acreage. Soybean acreage has steadily expanded in Manitoba, but field pea acreage has declined throughout the Prairies. In Ontario and Quebec, soybean acreage already exceeds corn acres suggesting that there is little room for further expansion of soy acres in the rotation and expansion would likely have detrimental effects to soil health and soil carbon storage.

Considerations

- Significant increases in pulse acreage will require both improvements in disease management through crop breeding and market development. These are longer-term initiatives. In the short-term, grain and oilseed legume acreage will fluctuate in response to market forces.
- Current N management protocols such as 4R Climate Smart, VM 22, or NMPP do not use a rotational approach that credits an increase in legumes in rotation and the overall reduction in N_2O through the rotational cycle. This needs to be rectified so voluntary and regulatory C markets reward growers who increase legume acreage and frequency in their rotations.

Additional BMPs Not Covered by OFCAF

There are several BMPs that are not explicitly covered in either the discussion paper or under OFCAF funding. The role these BMPs can play in reducing emissions needs to be considered going forward. The two we considered in this study are variable rate and section control.

Variable Rate

Variable rate allows growers to match fertilizer applications to variations in yield potential at the subfield level. While there are many different systems for creating production zones and assigning N rates at the subfield level, those that account for variability in factors that affect N availability are most likely to reduce N_2O emissions. For example, reducing N rates in areas that are yield limited due to soil quality issues or moisture availability (too wet or too dry) will match N availability with crop uptake and prevent nitrate residuals that could feed N_2O emitting process from accumulating. This also applies to areas in fields with higher mineralization potential. Typically soil organic matter and mineralization potential increases downslope. Lower slope positions may mineralize significantly more N over the growing season and require less fertilizer N to achieve their yield potential than mid and upper slope positions.

Considerations

- Variable rate has considerable potential to reduce overapplication in areas of fields with lower yield potential and prevent accumulation of residual nitrate.
- Variable rate also has potential to reduce losses from high yield potential areas when the higher mineralization rates in those areas are accounted for in formulating the N rate.
- VR may reduce N_2O emissions by lowering total N use for the field as well as by preventing build-up of residual nitrate in areas with reduced N uptake due to lower yield potential.
- Although it is hard to gauge, anecdotally many growers, particularly those with direct seeding equipment, have VR capability that is unused or the equipment can be upgraded for VR.
- Further research on the effects of VR on N_2O emissions is required so that we more fully understand the potential of this BMP in on-farm climate change mitigation.

Section Control

Background

Section control combined with guidance systems can reduce overlap in N applications and reduce total N use at the field level. Overlapped areas receive N in-excess of crop demand and the excess N will result in higher N_2O emissions during nitrification and be susceptible to losses through denitrification and leaching. Nitrous oxide emissions increase exponentially once crop demand is exceeded, consequently N_2O emissions per unit of N applied are likely to be substantially higher in overlap areas compared to the rest of the field. The amount of overlap with conventional application equipment will depend on the width of the equipment, the number of obstacles in the field, and the way the operator handles potential overlap areas like headlands. Consequently, overlap may range from as low as 2% in square fields with no obstacles seeded with a 40 ft drill up to 25% in a field with large obstacles seeded with a 100 ft drill.[21] Depending on the complexity of the required field path, and width of the controlled sections overlap can be cut in half or more.

Considerations

- In addition to reducing N fertilizer use and reducing N_2O emissions, section control can reduce over application of other fertilizer nutrients as well as seed. These additional savings help reduce the average cost per tCO_2e of emission reduction.
- The effectiveness of section control as an emission reduction BMP will be very landscape dependent. Farms with irregular fields and numerous obstacles such as pothole sloughs will benefit more than farms with regular shaped and obstacle free fields.
- Growers will need to map their overlap and estimate potential savings against equipment costs to determine if section control is a viable option. Adoption of section control on individual farms will likely coincide with equipment turnover as growers replace air drills and seeders.

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[21] Evaluation of Emission Reductions and Cost Savings in Sectional Control Air Seeders, Drills, and Sowing Equipment Across the Canadian Prairies Alberta Pulse Growers Commission.

- Current methodologies for estimating N_2O emissions are based on total N applied per field and will tend to under-estimate the emission reduction in overlap areas receiving two or more times the prescribed N rate.

Section Summary

The effectiveness of the BMPs discussed above will vary significantly regionally and from farm to farm and even field to field within regions. While it is important to insure that BMPs are backed by good science that verifies their capability to reduce fertilizer N_2O emissions, it's also important to recognize that some technologies not considered in the discussion paper may have substantial reduction potential. Some care should be taken in designing policy that is too prescriptive of technologies as it will stifle innovation.

In the following section, the costs of BMP implementation and the expected emission reductions are modelled at a regional level out to 2030. Not all the BMPs discussed above were included in the modelling exercise. The BMPs chosen included enhanced efficiency fertilizer, split application, soil testing, variable rate, and section control. These BMPs were chosen because they are directly related to fertilizer N management are generally applicable in all major cropping systems, and, with the exception of section control, are included as BMPs in the current version of the 4R Climate Smart Protocol.

Financial Analysis and Emission Reduction of 4R Practices

The 4R financial analysis and emission reduction modeling calculated the reduction of fertilizer emissions and the cost of implementing select 4R best management practices (BMP) used to decrease those emissions. These calculations were completed for 5 regions in Canada – Quebec, Ontario, Wet Prairie East, Wet Prairie West, and Dry Prairie. The total acres of crops studied in these regions was 59.3 million acres.[22] Since a regional approach was used to calculate the broadscale financial effects of BMPs at various adoption rates within those regions, it is important to note that the analysis does not reflect the cost of implementing the BMPs at an individual farm level. The per acre cost at farm level would be higher than the regional analysis because the adoption rates used in the regional models were less than 100%, meaning that not all acres were incurring the cost of the BMPs. These costs were averaged over the entire region to achieve a per acre cost for the region and as a result they are lower than would be the case on an individual farm equivalent.[23]

The regional analysis focused on the macroeconomics of adoption over time and what it would mean for the regional farm economy projecting out to 2030. Three scenarios were analyzed: the first with increasing adoption rates and no crop yield increase, a second with the same adoption rates as the first scenario but with increasing crop yields, and finally a scenario with increasing crop yields and adoption rates that would be required to reach a 30% emission reduction.

Financial Methodology

An Excel model was developed to calculate the financial impacts of 4R BMPs over a 10-year time period on selected field crops in the five regions.[24] The model calculated nutrient usage, nitrous oxide from nitrogen fertilizer, and the cost of implementation of various 4R best management practices (BMP). The model calculated a weighted per acre budget for each region and returned revenue, operating and

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[22] Appendix 2 shows the breakdown by crop in each region and other summary information on assumptions used.

[23] The integration of the N management BMPs used in this study with rotational and land management strategies were examined in a supplemental study using model farms in each region. The results of the supplemental study examining cost/benefit at the individual farm level will be released in a second report.

[24] The model is easily adaptable and can be used to explore alternative scenarios at the regional, ecodistrict or farm level.

overhead costs, contribution margin and net income per acre for each crop based on the chosen adoption rates of the BMPs. The per acre metrics were rolled up by crop acres to provide regional totals.

Statistics Canada data for crop prices, yield, and acreage were used from the 2017-2021 crop years supplemented with 2022 price data where available.[25] A 5-year Olympic average[26] was used to estimate the 2022 crop year yield and acreage. This data was available on a census division level. Regional data sets were developed for Ontario, Quebec, Wet Prairie East and Wet Prairie West, and the dry prairie using Statistics Canada census division data.[27]

Ontario and Quebec are treated as single regions using provincial boundaries while the Prairie Provinces were split out into three regions:

- Dry Prairie – the brown and dark brown soil zones of Alberta and Saskatchewan. This region tends to have higher moisture deficits and lower emissions than other Prairie regions.
- Wet Prairie West – the black and gray soil zones of Alberta and Saskatchewan. This region has lower moisture deficits than the dry prairie but tend to be shorter season and cooler than the Wet Prairie East.
- Wet Prairie East – primarily the black soil zone of Manitoba characterized by lower moisture deficits compared to the Dry Prairie but a longer warmer growing season compared to Wet Prairie West.

Crop production costs from provincial agricultural ministries were used to develop the 2022 crop budgets. Provincial data for Quebec was sourced from the Quebec Reference Center for Agriculture and Agri-food (CRAAQ)[28]. Fertilizer costs and the cost of implementing the 4R practices were calculated by the model along with the adjustment of other costs such a seed which is impacted by BMP implementation.

Crop budgets were calculated separately for each region and then combined to create a weighted average budget that represented the cost per acre for the entire region. The weightings were based on Statistics Canada harvested acreage for each region.

Baseline scenarios were developed for each region using the 2020 adoption rates of the BMPs which were used to compare the economic impact of 4R implementation.

Contribution margin (revenue minus variable costs) was used as a key economic indicator along with the BMP and fertilizer costs for the financial analysis. While net income was calculated as part of the analysis, contribution margin is the more useful comparator between regions. This is because net income includes fixed costs such as depreciation, land and building costs which can vary widely between individual farms and regions of Canada. To fairly assess BMPs that required upgrades in equipment which are considered a fixed cost, these costs were amortized on a per acre basis and added as an variable expense instead of a fixed expense.

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[25] Statistics Canada. Table 32-10-0359-01 Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units

[26] A five year Olympic average is calculated by removing the highest and lowest numbers and taking an average of the remaining three.

[27] Statistics Canada. Table 32-10-0002-01 Estimated areas, yield and production of principal field crops by Small Area Data Regions, in metric and imperial units

[28] https://www.craaq.qc.ca/

How the model works

The model allows for a wide number of variables to be adjusted and analyzed. All costs, yields, and prices by crop can be adjusted by year.

Adoption rates: the model allows adoption rates of BMPs to be adjusted for each crop which impacts both the emission calculations and the budget costs. For example, if a BMP costs $10 per acre and the adoption rate is 50% then $5 would be entered into the budget for that crop. The $5 would represent the average cost over the entire acreage that was being analyzed for that crop. The adoption rate is adjustable on an annual basis.[29]

Adoption rates were increased on an annual basis at what could be considered an optimistic but realistic level especially when considering some of the low pre-2020 adoption rates. In most cases, adoption rates were similar for each N using crop in the region. For example, on the dry prairie adoption rates for EEF in canola was the same as the adoption rate in spring wheat and barley. As an N_2O reduction strategy at a regional level, it may be more effective to increase adoption of EEFs in canola with its high N rates relative to the other crops. For the most part a combination of data sources was used in setting the 2020 adoption practices that became the starting point for increased adoption. Primary among them was the Fertilizer Use Surveys conducted in 2019 and 2020.

Fertilizer calculations: the model calculated actual nutrient requirements per acre times fertilizer cost for each individual scenario. The model allows various combinations of fertilizer type and application method such a split application. In addition to the baseline, there are five scenario options for 4R practices. These practices impact the amount and efficiency of fertilizer use based on the parameters entered into the model. They include enhanced efficiency fertilizer, split-application, variable rate application, soil testing, section control and two combinations of BMPs. A variety of data sources were used to set the regional N, P, K, S fertilizer rates for each crop again primarily relying on the 2019 and 2020 Fertilizer Use Surveys.

Fertilizer Cost: current fertilizer prices are at record highs having increased in some cases over 100% in the past 2 years. Developing accurate fertilizer cost pricing proved to be difficult because of the proprietary nature of the industry's price data and the wide geographic area that was being studied. In addition to that posted prices of fertilizer when available are not always what producers pay. Therefore, an estimation of the 2022 fertilizer price was done using a number of sources:

- Retail fertilizer prices from the US, adjusted by exchange rate[30],
- Statistics Canada Farm Input Price Index (FIPI) [31],
- Ontario crop input survey,
- Informal inquiries of crop input suppliers.

The combination of these sources allowed for an approximate costing of fertilizer; however, there could be significant variances between product types and the timing and location of purchases. The model allows the 2022 price to be adjusted forward for the 2023-2030 years on an annual basis.

For specialized products such as enhanced efficiency fertilizers where a posted price was difficult to obtain urea 46% was used a base price and multiplied by a percentage increase to arrive at a reasonable estimated price for the specialized products.

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[29] Adoption rates by region and crop are shown in Appendix 3.

[30] https://www.dtnpf.com/agriculture/web/ag/crops/article/2022/07/13/urea-leads-fertilizer-prices

[31] Statistics Canada. Table 18-10-0258-01 Farm input price index, quarterly

Because of the difficulty in predicting future fertilizer price swings, a three-year average of 2020-2022 prices was created and the price held constant through to 2030 for the analysis. As noted in the analysis section fertilizer cost impacts the net benefit of the BMP implementation. Lower fertilizer costs will reduce the net benefit cost of the BMP.

BMP Machinery Cost: additional machinery costs incurred when implementing a particular best management practice were calculated by taking the estimating the cost of the additional equipment, amortizing it over 15 years and then dividing it by the average farm size for the region. In Western Canada 3,840 acres was used as an average farm size when calculating the per acre cost for additional farm machinery. For example, if the additional equipment cost $150,000 and was amortized over 15 years, the per acre cost was calculated by dividing $150,000 by 15 years divided by 3840 acres. In Ontario and Quebec, the average farm size used was 1200 acres.

Land costs: all land costs that may have been included in the operating costs of provincial budgets were moved into the overhead or fixed cost section of the budgets. This was because, as stated above, these can vary significantly between farm with different financial structures and in different geographic regions. Crop budgets from western provincial governments included land costs and these were used in the model. In Ontario and Quebec estimates of land costs were made using Farm Credit Canada farmland survey data[32].

Crop prices: prices obviously have a large impact on contribution margin and farm profitability. In 2022 many crops are at record price levels. While it is impossible to accurately predict future prices it is reasonable to expect that these prices will cycle lower in the coming years. For that reason, the model was set to lower the price of all crops by 3.5% per year resulting in prices in 2030 that were 5-20% higher than the 2020 prices.

Operating and overhead costs: operating costs were set in the model to increase by 5% per year for 2023-24 and between 3-4% for 2025-30. Overhead costs were programmed for a 3% increase for 2023-24 and between 2-2.5% these for 2025-30. These rates are consistent with historic increases[33] over the past 5 years and are conservative given the current inflation rates.

Nitrous Oxide Emission Methodology

Emissions from fertilizer were modelled using methods and data derived from the 2022 National Inventory Report and the 4R Climate Smart Protocol. [34,35] In brief, the emission factors required for calculating direct fertilizer emissions were regionalized using a weighted mean approach. The direct emission factor[36] for each ecodistrict in the region where fertilizer N was applied to annual crops was the input data and the quantity of fertilizer N applied in each ecodistrict was used as the weighting factor. A similar approach was used to determine the leaching fraction in each region and estimate N loss from leaching and runoff. Emissions from leached N were calculating using the IPCC default emission factor (0.0075 kg N_2O-N/kg N applied) following the 2022 NIR. Volatilized N was estimated using the volatilization coefficients ($FRAC_{GASF}$) outlined in the 2022 NIR. Indirect emissions from volatilized N were estimated using the current IPCC emission factors for drier regions (0.005 kg N_2O-

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[32] https://www.fcc-fac.ca/en/knowledge/economics/farmland-values-report.html and https://www.fcc-fac.ca/en/knowledge/economics/2021-farmland-rental-rates.html

[33] Statistics Canada. Table 18-10-0258-01 Farm input price index, quarterly

[34] The detailed ecodistrict level data on N fertilizer use and updated emission factors were provided by ECCC following release of the 2022 NIR in April 2022.

[35] Further details on the equations use to estimate N_2O are provided in Appendix 1.

[36] Referred to as EFeco in the 4R Climate Smart Protocol or EF_base in the 2022 NIR.

N/kg N applied) in the prairie scenarios and the wetter region factor (0.014 kg N_2O-N/kg N) for Ontario and Quebec.

Within a region, baseline fertilizer N_2O emissions for each year were calculated as above using the average per acre N rate after adjustment for each BMP-crop combination. For example, the rate reduction assigned for use of an EEF was 10% to account for improved nitrogen use efficiency. If the adoption rate for EEFs was 50% for wheat in the region and the base N rate was 100 lb/N acre, the rate would adjusted downward by 5 lb N/acre. Once the baseline N_2O emissions were estimated based on the adjusted 95 lb N/acre rate, it was multiplied by a reduction modifier to account for the source, time, place effects of the BMPs. In the case of an EEF, the reduction modifier used was 25%. Since, only 50% of the crop acres were treated with a BMP the reduction modifier was discounted to 12.5%. This resulted in an overall reduction in N_2O emissions of approximately 35% for use of an EEF but only 17.5% for the crop in the region at a 50% adoption rate. The delta between the BMP scenarios and a business as usual (BAU) scenario were used to estimate emission reductions and cost per tonne of reduction.

The GHG calculations were integrated into the financial model to allow simultaneous calculation of financial and GHG data including cost per tonne of reduction estimates.

Financial Analysis of Regions

Overall Financial Impact on Farm Income

This section provides an overview of the whole farm financial results of the analysis for each region for the initial no yield increase and yield increase scenarios. The BMP adoption rates used for each region are in Appendix 3.

Analysis of revenue, operating expenses, contribution margin, fixed expenses and net income based on the various adoption rates of the 4R best management practices was completed over the 10-year period. The change in these metrics was influenced by the level of adoption of the BMPs in each region and while these are expressed in a per acre cost these represent the weighted average of the entire region and not what an individual farm might experience. For example, an adoption rate of a particular BMP of 50% means that only half the acres in that region are using the practice and therefore only 50% of the cost of implementing that practice is calculated in the budget for the region.

Table 2 summarizes the parameters that were used in the model to simulate changes in prices and costs between 2023 to 2030. These values where used in the no yield and yield increase scenarios.

Table 2. Model Parameters for Crop Price, Yield, Operating Costs and Fixed Costs.

	2023	2024	2025	2026	2027	2028	2029	2030
CROP PRICE	-3.5%	-3.5%	-3.5%	-3.5%	-3.5%	-3.5%	-3.5%	-3.5%
YIELD	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
OPERATING COSTS	5.0%	5.0%	4.0%	3.0%	3.0%	2.0%	2.0%	2.0%
FIXED COSTS	3.0%	3.0%	2.5%	2.5%	2.5%	2.0%	2.0%	2.0%
FERTILIZER RATE CHANGE	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

No Yield Increase Scenario

Contribution Margin - In all regions, contribution margin declined as expected as the price declined to just above 2020 levels. 4R best management practices are included in the variable costs and therefore contribute to the declining contribution margin. What is clear is that this is a negative trend. In all regions studied the contribution margin fell between $225 and $299 per acre from 2022 to 2030. These are large decreases. Contribution margin supports the payments to land, machinery and return to equity or owners wages.

Net Income - In four of the five regions the net income became negative during the last three years of the analysis. Only the Wet Prairie East region maintained a positive net income throughout the 10-year period. Fixed expenses impact net income and can be highly variable between different farms, therefore the net income figures should be viewed with some caution. However, declining prices and upward cost pressure clearly will put pressure on margins and net income. Should they unfold as modeled in our analysis it would result in lower net incomes in all regions, and this could make producers more hesitant to incur additional investment costs in 4R BMPs.

Table 3. Ontario Financial Indicators.

Financial Indicators (per Acre)	2022	2030	Change
Revenue	$ 1,013	$ 795	$ (218)
Operating Expenses	$ 472	$ 541	$ 69
Contribution margin	**$ 541**	**$ 253**	**$ (287)**
Fixed Expenses	$ 288	$ 349	$ 61
Net Income	**$ 253**	**$ (95)**	$ (348)

Table 4. Quebec Financial Indicators.

Financial Indicators (per Acre)	2022	2030	Change
Revenue	$ 914	$ 687	$ (227)
Operating Expenses	$ 465	$ 537	$ 72
Contribution margin	**$ 449**	**$ 150**	**$ (299)**
Fixed Expenses	$ 235	$ 285	$ 50
Net Income	**$ 214**	**$ (135)**	$ (349)

Table 5. Wet Prairie East Financial Indicators.

Financial Indicators (per Acre)	2022	2030	Change
Revenue	$ 738	$ 555	$ (183)
Operating Expenses	$ 354	$ 405	$ 51
Contribution margin	**$ 384**	**$ 150**	**$ (234)**
Fixed Expenses	$ 82	$ 100	$ 17
Net Income	**$ 302**	**$ 50**	$ (252)

Table 6. Wet Prairie West Financial Indicators.

Financial Indicators (per Acre)	2022	2030	Change
Revenue	$ 719	$ 541	$ (178)
Operating Expenses	$ 399	$ 460	$ 61
Contribution margin	**$ 320**	**$ 81**	**$ (239)**
Fixed Expenses	$ 120	$ 146	$ 26
Net Income	**$ 200**	**$ (65)**	$ (264)

Table 7. Dry Prairie Financial Indicators.

Financial Indicators (per Acre)	2022	2030	Change
Revenue	$ 683	$ 514	$ (169)
Operating Expenses	$ 353	$ 408	$ 55
Contribution margin	**$ 330**	**$ 106**	**$ (225)**
Fixed Expenses	$ 102	$ 124	$ 22
Net Income	**$ 229**	**$ (18)**	$ (247)

Figures 6 through 10 show the financial overview of the 5 regions. The trends are very similar with the declining contribution margin and net income. While net income varies some between the regions the contribution margin change is very consistent.

Figure 6. Ontario Revenue, Operating Expenses, Contribution Margin and Net Income.

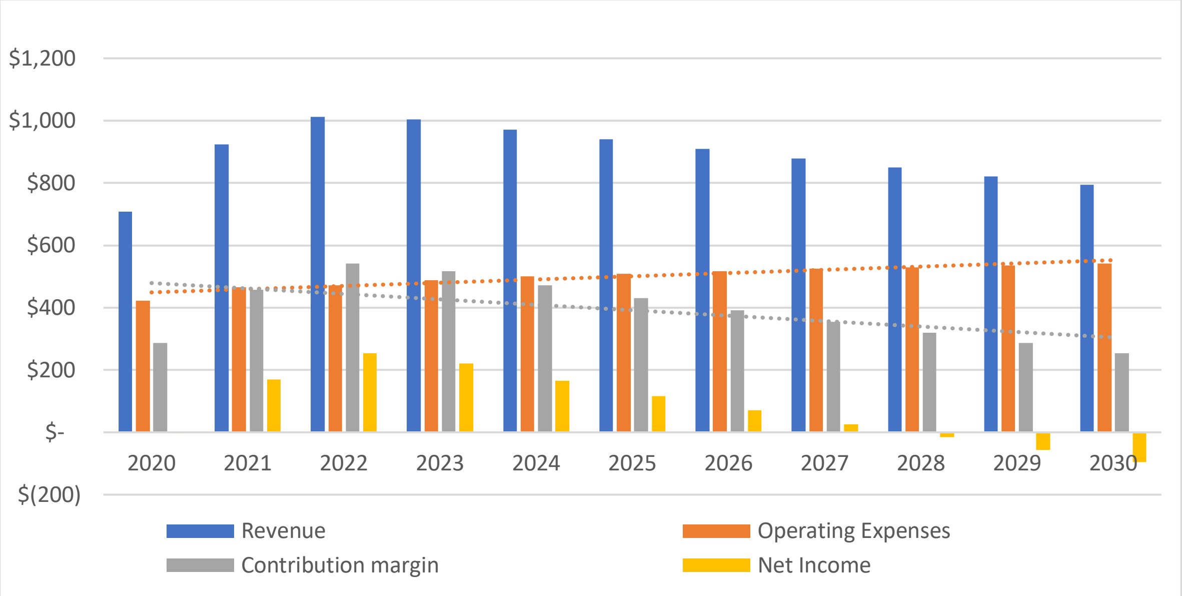


Figure 7. Quebec Revenue, Operating Expenses, Contribution Margin and Net Income.

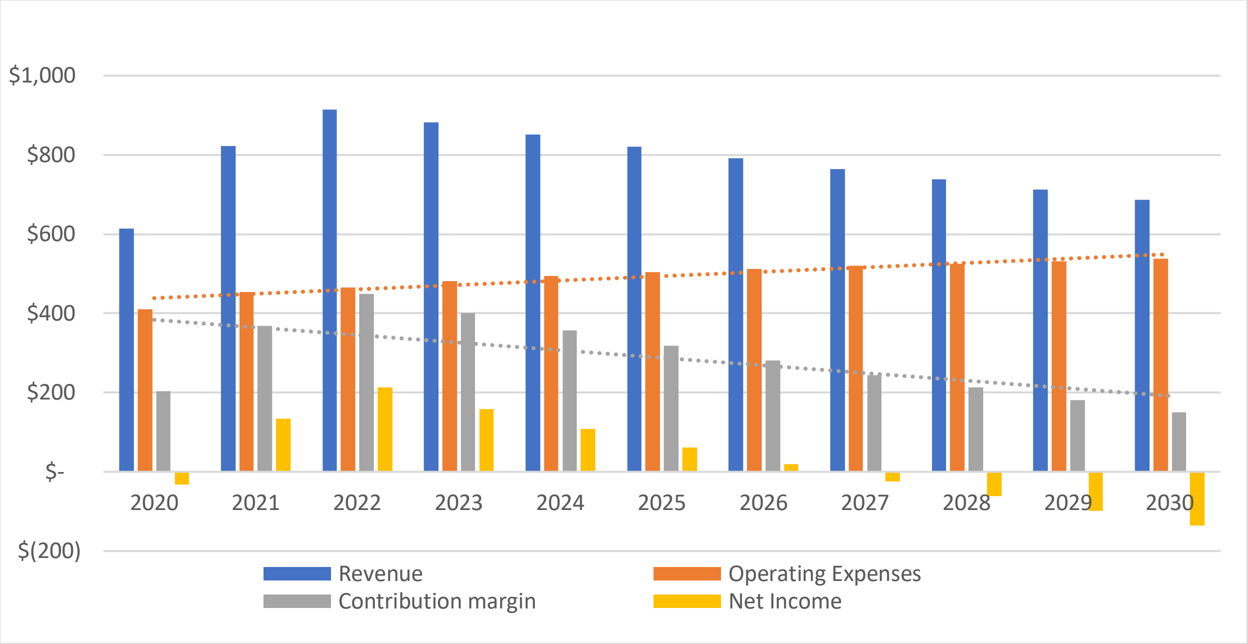


Figure 8. Wet Prairie East Revenue, Operating Expenses, Contribution Margin and Net Income.

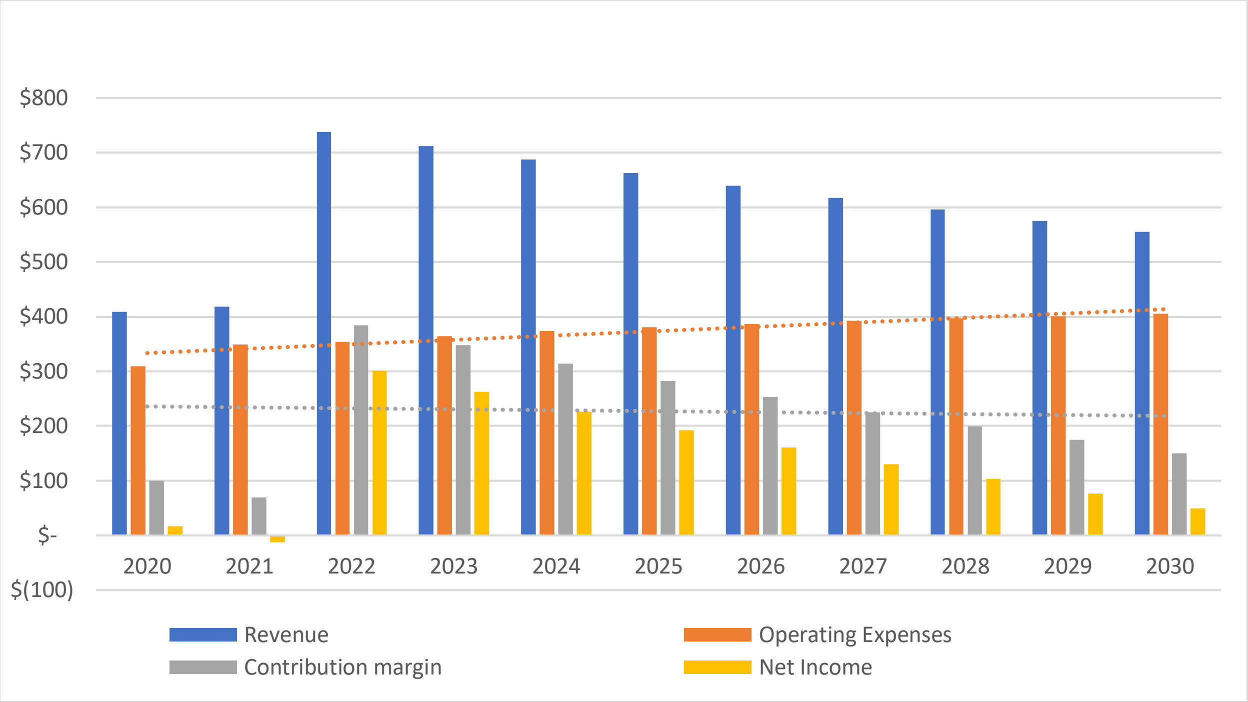


Figure 9. Wet Prairie West Revenue, Operating Expenses, Contribution Margin and Net Income.

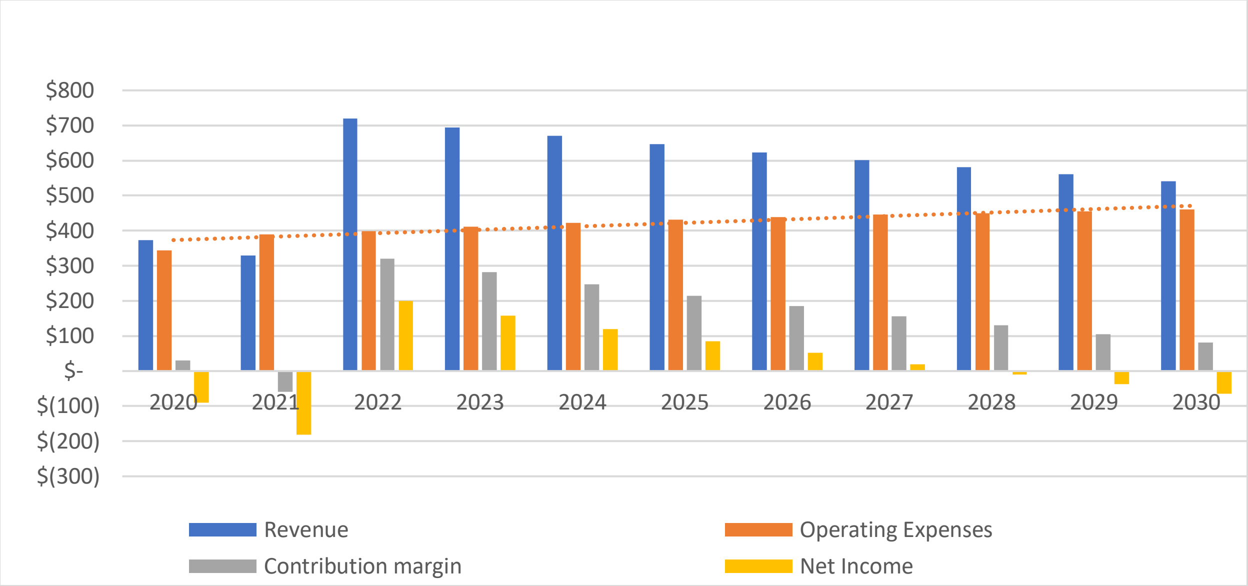
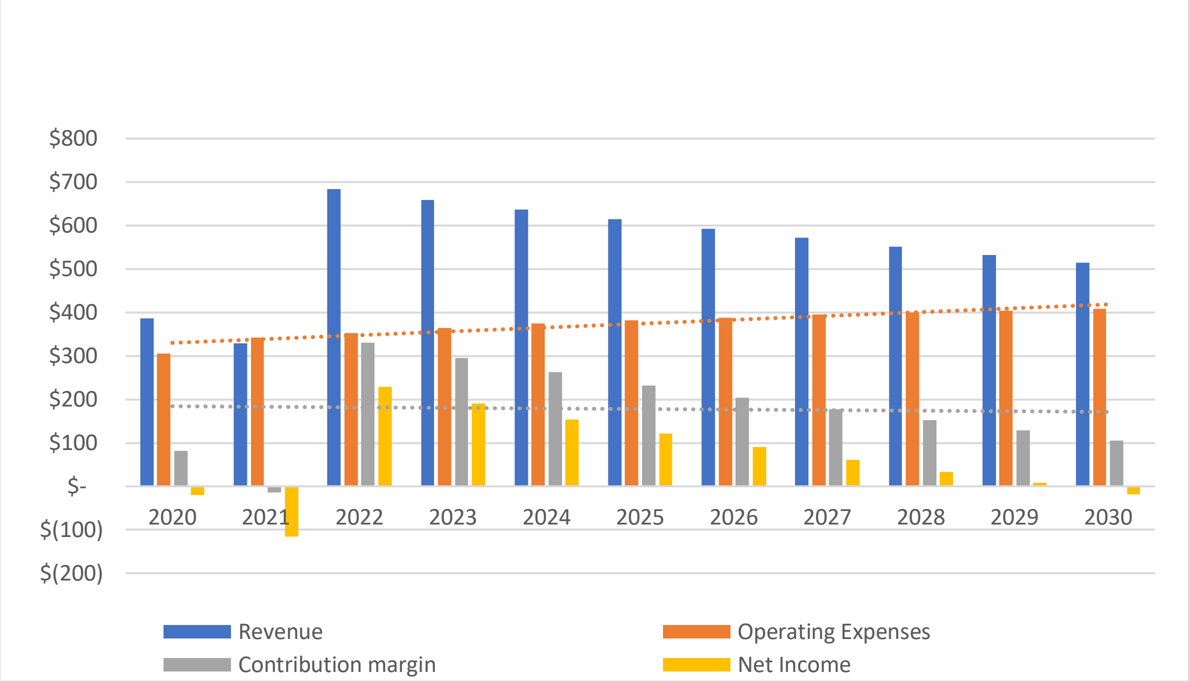


Figure 10. Dry Prairie Revenue, Operating Expenses, Contribution Margin and Net Income.



Nitrogen Change

Table 8 shows the change in nitrogen from the baseline after 4R BMPs were adopted at the various rates shown in Appendix 3. As expected, the western regions had the highest total deductions of nitrogen use simply because of the large acreages. In total over the 10-year period the analysis estimated that 1.4 billion tonnes of nitrogen could be reduced. It is important to note this is based on no yield increases. Much of the reduction would come from replacement of conventional sources such as urea with enhanced efficiency sources such as double inhibited, or polymer coated urea that command a premium in the marketplace. As a result, total tonnage reductions do not directly translate into reduced revenues for the fertilizer industry.

Table 8. Nitrogen Change

	ONTARIO	QUEBEC	WET PRAIRIE EAST	WET PRAIRIE WEST	DRY PRAIRIE	TOTAL
NITROGEN CHANGE						
CHANGE IN LBS PER ACRE OF NITROGEN FROM BASELINE AT 2030	(5.37)	(5.75)	(8.99)	(10.25)	(8.40)	
PERCENTAGE CHANGE	-6.4%	-7.1%	-8.7%	-9.3%	-9.3%	
CHANGE IN TOTAL TONNES OF NITROGEN IN 2030 FROM BASELINE	(14,993)	(6,142)	(33,552)	(118,111)	(65,329)	(238,128)
CUMULATIVE TONNES OF NITROGEN CHANGE	(75,007)	(30,521)	(194,428)	(684,496)	(378,346)	(1,362,798)

Table 9 shows the estimated cost of implementing the 4R BMPs at the adoption rates selected for the 2030 year. The total cost represents the estimated amount spent for implementing all BMPs in 2030. The net cost is the total costs less the 2020 baseline amount or amount spent on the BMPs at the baseline adoption rates in 2020. The last line in the table shows the total cost net of the savings from the reduction of fertilizer and seed. In the no yield increase scenario, the change in contribution margin is the reverse of the net BMP cost, since all the costs and revenues in the baseline scenario are identical except for the higher costs of the BMPs and saving from fertilizer and seed. For example, in Ontario the net cost of BMP implementation in 2030 is $1.3 million, resulting in a equivalent $1.3 million decline in contribution margin.

Ontario has the lowest cost based on the adoption rates selected for that region. The fact that corn is a high nitrogen user means that on a percentage basis the model estimated larger reductions of nitrogen which resulted in a larger proportional savings that can be used to offset the cost of the BMPs.

Table 9. Cost of BMP Adoption in 2030 with No Increase in Crop Yield and Realistic Adoption Rates.

Cost of BMP Implementation ($millions)	Ontario	Quebec	Wet Prairie East	Wet Prairie West	Dry Prairie	Total
Total BMP cost of implementation in 2030	56	24	75	208	131	495
Total BMP cost of implementation in 2020 baseline	24	10	20	49	32	136
Net cost of implementation (total - baseline)	32	14	55	157	98	357
Total BMP cost net of fertilizer and seed in 2030	1.3	3.7	20.3	48.4	35.6	109.2

In total, farmers would be paying a yearly aggregate of $495 million in 2030 to implement or maintain BMPs on farm. This would be $357 million per year more than the estimated 2020 spend on BMPs. The projected savings in fertilizer costs and seed costs would reduce the deficit by $248 million to $109 million resulting on a net spend of $109 million. This additional $109 million in unrecovered costs would be disproportionately carried by the farmers who implement BMPs. This no yield scenarios suggests that without opportunity for yield increases and revenue growth, fertilizer cost savings alone are insufficient to cover the costs of BMP adoption even when substantial N rate reductions are applied.

The estimated cumulative costs of BMP adoption from 2020 to 2030 for the 5 regions was estimated at \$3.4 billion with net costs of \$1.9 billion dollars (Table 10). When the savings for reduced fertilizer and seed costs were factored in the cumulative cost falls to \$765 million. As noted above, the Ontario region shows the greatest cost effectiveness in reducing nitrogen rates and offsetting the cost of BMPs through saving through N fertilizer costs. Keep in mind that the \$2.9 mission in cumulative cost in Ontario is based on substantial reductions in fertilizer N use without yield decline. The earlier figure of 5.37 lb N/acre in N application is averaged over all corn, soybean, and winter wheat acres in Ontario. The actual reduction in N use on N fertilized crops where BMPs were adopted would be considerably higher and could potentially result in yield declines. Lower yield would reduce revenue and put further downward pressure on the contribution margin of farms adopting BMPs.

Table 10. 10-Year BMP Implementation Costs.

10-year BMP Costs (\$ millions)	Ontario	Quebec	Wet Prairie East	Wet Prairie West	Dry Prairie	Total
10-yr cumulative cost of BMP implementation	427	184	521	1,401	888	3,420
10-yr cumulative cost net of baseline cost of BMP implementation	161	78	298	846	528	1,912
10-yr cumulative net cost of BMP - less fertilizer and seed cost change	2.9	22.5	139	355	245	765

Keep in mind that the \$2.9 mission in cumulative cost in Ontario is based on substantial reductions in fertilizer N use without yield decline. The earlier figure of 5.37 lb N/acre in N application is averaged over all corn, soybean and winter wheat acres in Ontario. The actual reduction in N use on N fertilized crops where BMPs were adopted would be considerably higher and could potentially result in yield declines. Lower yield would reduce revenue and put further downward pressure on the contribution margin of farms adopting BMPs.

At the adoption rates used in the no yield increase scenario, the cumulative reduction in fertilizer N_2O over the 10-year period was estimated at 14.5 $MtCO_2e$ (Table 11). The reduction from the baseline 2020 to 2030 year was estimated at 2.5 $MtCO_2e$. While this a substantial reduction, it is well short of the 30% reduction target of 3.5 MtCO2e.

The estimated cost per tonne for removal in 2030 would range from \$4.05 in Ontario to \$59.62 in the Dry Prairie region averaging out at \$43.68. Calculating this on a per acre basis the cost would range from \$5.00 per acre to \$28.10. Again, noting that the cost per acre is spread over all crop acres not just those on which BMPs were applied and this cost per tCO2e is after fertilizer savings.

Table 11. Cost of Fertilizer N_2O tCO_2e Reduction No Yield Increase Scenario.

Cost of Fertilizer N_2O tCO2e Reductions	Ontario	Quebec	Wet Prairie East	Wet Prairie West	Dry Prairie	Total
10-yr cumulative fertilizer N_2O tCO_2e reduction from 2020 baseline (tonnes)	(1,580,889)	(1,074,812)	(2,388,051)	(5,830,333)	(3,555,585)	(14,429,671)
Fertilizer N_2O tCO_2e Reduction in 2030 from 2020 baseline (tonnes)	(311,781)	(213,622)	(400,621)	(978,010)	(596,880)	(2,500,914)
Average net cost per tonne for removal in 2030	\$4.05	\$17.42	\$50.56	\$49.50	\$59.62	\$43.68
Average net cost per acre for removal in 2030	\$5.00	\$47.59	\$46.51	\$25.54	\$28.10	

The 2022 NIR estimated the total N_2O emissions from fertilizer N at 11.8 $MtCO_2e$ in the 2020 baseline year based on a total fertilizer N application of 2.91 million metric tons. In this study, our baseline 2020 emissions were estimated at 11.7 MtCO2e and total fertilizer N applied in the regions modelled was 2.64 million metric tonnes. The reduction from our 2020 baseline amounted to 21%. This 21% reduction was achieved by increasing adoption of individual BMPs four to eight-fold depending on the BMP and region; applying substantial reductions in N rates based on the BMPs increasing NUE; and using moderately aggressive reduction modifiers to account for source, time, place effects. The 21% reduction from the 2020 baseline is in-all-likelihood an over generous estimate of what can be achieved by 2030.

The Impact of Yield Increase

In the results presented to this point, the yield of all crops was kept flat from 2022 through 2030. This allowed the potential effects of BMP adoption on decreasing nitrogen application rates be isolated in the analysis.

However, as new varieties continue to be developed and crop management improves, the yield potential of crops will increase. Producers will seek to exploit this additional potential and increase their yields to offset rising production costs and meet market demands. Yield increase and increased intensity of production have been a long-term trend in Canadian and global crop production and have offset the inflationary trends in operational and fixed costs. Consequently, crop yields will continue to increase as they have in the past and fertilizer application rates are likely to increase correspondingly. To examine the potential effects of this trend on fertilizer N_2O emissions, the yields of N fertilized crops were increased incrementally out to 2030 in the model and N rates moderately increased to support the additional yield. Table 12 shows the increased yield and nitrogen rates used in the model under the increased yield scenario. Crop and fertilizer prices, BMP adoption rates, BMP associated rate reductions and reduction modifiers were kept the same as the no yield scenario.

Table 12. Parameters Used to Model the Economic and Emission Impacts of Yield Increases.

	Yield increase per year	Yield - bushels per acre		Nitrogen - lb per acre		lb of N increase per bu
Ontario		*From*	*To*	*From*	*To*	
Corn	1.86%	165.6	192.0	160	190.3	1.15
Winter Wheat	0.75%	81.5	86.5	130	137.3	1.45
Quebec						
Corn	1.50%	149.2	168.1	150	171.7	1.15
Winter & Spring Wheat	0.75%	48.5	51.5	90	94.3	1.45
Oats	0.75%	66.6	70.7	80	83.5	0.85
Barley	0.75%	58.7	62.3	80	83.9	1.08
Wet Prairie West						
Canola	2.80%	41.7	52.0	130	150.9	2.03
Wheat	0.75%	51.5	54.7	100	105.8	1.82
Barley	0.75%	69.7	74.0	80	84.6	1.08
Wet Prairie East						
Canola	2.77%	41.8	52.0	130	150.7	2.03
Wheat	0.75%	59.6	63.3	100	106.7	1.82
Barley	0.75%	76.6	81.3	80	85.1	1.08

Dry Prairie						
Canola	2.80%	36.6	45.6	115	133.4	2.03
Durum Wheat	0.75%	34.3	36.4	100	103.8	1.82
Barley	0.75%	60.3	64.0	80	84.0	1.08

Tables 13 show the impact of increasing yields and nitrogen application rates across all region compared to the no yield increase scenario. The analysis represents all the modelled crop acres in each region including soybean acres in Ontario and Quebec and field pea, lentil, and soybean in the prairie region. Since N fertilizer is not applied to these crops except for the small amounts included in phosphorus and sulphur fertilizers, the nitrogen rate change shown is lower than presented in Table 12.

The results show that when yields and corresponding nitrogen rates are increased, nitrogen use for all the regions change from a net decrease of 238 thousand metric tonnes N to a net increase of 48 thousand metric tons N in the 2030 year. Because more N was applied relative to the 2020 baseline but the adoption rates were held constant, the net fertilizer emission reductions are lower compared to the no yield increase scenario. Fertilizer N_2O reductions decreased from 2.5 MtCO2e to 1.6 MtCO2e in the 2030 year.

The cost of BMP implementation remained the same in both the no yield and the yield increase scenarios, but emission reductions were lower resulting in a substantial increase in cost per tCO_2e reduced compared to the no yield scenario. In Ontario the cost rose from $4.05 to $74, in Quebec from $17 to $47, in Wet Prairie East from $51 to $113, in Wet Prairie West from $49 to $125 and in Dry Prairie from $60 to 123 per tCO2e removed.[37] On average the increase in cost of removal increased from $44 to $113 per tCO2e.

The cost of BMPs net of fertilizer and seed increased to a total of $184 million in 2030 as yield increased, up from $109 million. This might seem counter intuitive because the adoption rates did not change. The explanation is that with higher nitrogen use the fertilizer N reduction from the BMPs did not compensate as fully for the increased fertilizer rates. BMPs costs were offset by a 238 thousand metric ton reduction in fertilizer N in the no yield scenario. In the yield increase scenario, the same BMP costs were not offset as fertilizer N application increased by 48 thousand metric tons relative to the 2020 baseline. Thus, the offsetting fertilizer cost reductions from the BMPs were smaller and the cost of BMPs net of fertilizer and seed costs were higher.

The most dramatic impact of yield increases was on the contribution margin. The estimated contribution margins in 2030 increased in all regions with increases ranging from $48 to $83 per acre higher than the no yield increase scenario. This represents a total $4.3 billion increase in contribution margin or revenue for the combined regions in the 2030 year over the no yield scenario. On an annual basis this represents a significant increase in revenue for farmers and demonstrates the impact of increasing yield in helping producers to offset increasing costs.

Table 13. Total Effect of Increase Yield and Nitrogen Application Rates in All Regions.

	Total of all Regions	
Summary Results	**No Yield Increase**	**With Yield increase**
Nitrogen Change		

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[37] Results for the separate regions are included in Appendix 5.

Change in total tonnes of nitrogen in 2030 from 2020 baseline	(238,128)	47,936
Cumulative tonnes of nitrogen change	(1,362,798)	(77,511)
Cost of BMP Implementation ($millions)		
Total BMP cost of implementation in 2030	495	495
Total BMP cost of implementation in 2020 baseline	136	136
Net cost of implementation (total - baseline)	357	357
Total BMP cost net of fertilizer and seed in 2030	109	184
10 year BMP Costs ($millions)		
10-yr cumulative cost of BMP implementation	3,420	3,420
10-yr cumulative cost net of baseline cost of BMP implementation	1,912	1,912
10-yr cumulative net cost of BMP - less fertilizer and seed cost change	765	1,372
Cost of Fertilizer N_2O Reductions in units of tCO_2e		
10-yr cumulative fertilizer **N_2O** reduction from 2020 baseline	(14,429,671)	(10,359,799)
Fertilizer **N_2O** Reduction in 2030 from 2020 baseline	(2,500,914)	(1,634,966)
Average net cost per tCO_2e removal in 2030	44	113
Contribution Margin ($ millions)		
Change in contribution margin in 2030 from 2020 baseline	(109)	4,289

Impact of Yield Increase on Fertilizer Emissions

While yield increases accompanied by a modest increase in fertilizer N use had a highly positive effect on contribution margins, it unsurprisingly resulted in substantially smaller reductions in fertilizer emissions (Figure 10).[38] The lower emission reductions where largely driven by yield and N rate changes in high N use crops, notably corn in Eastern Canada and canola on the Prairies.

In all scenarios the estimated reductions in fertilizer emissions are a product of rate optimization (rates were reduced assuming higher NUE when BMPs were applied) and the emission reductions attributed to improved source, time, place (the reduction modifiers). The levels of BMP adoption were held constant between the yield increase and no yield increase scenarios. This suggests that in a yield increase scenario, BMPs would need to be implemented at a significantly higher rate to achieve total reductions similar to the no yield scenario.

Figure 10. Annual Fertilizer N_2O Reduction - Comparison Across all Regions.

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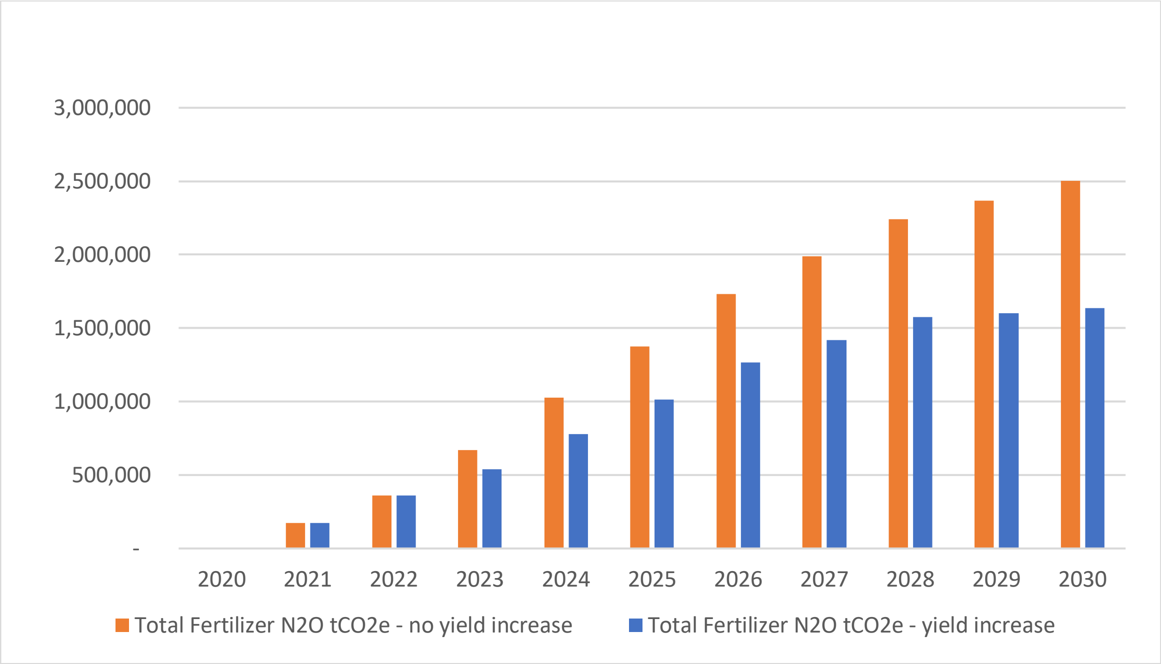
[38] The graphs for the individual regions are all very similar to Figure 10 and can be found in Appendix 5.



Adoption Rates Required to Achieve the 30% Emission Reduction Target.

Given that it is reasonable to assume that increased crop yields and higher nitrogen application rates will be required for farmers to remain profitable and meet the increasing global requirements for crop products, it was important to determine what levels of BMP adoption would be required to meet a 30% fertilizer emission reduction. This was estimated by increasing adoption rates iteratively using the same parameters used in the previous yield increase scenario until the 30% reduction was reached for the 2030 crop year.

In Ontario and Quebec, 100% of growers would need to adopt EEF use or split-application on their N fertilized crops plus additional BMPs such as VR and section control to reach the 30% reduction target for the modelled crops within the region (Table 14). Section control and EEF use were assigned the same N rate reduction (10%) and source, time, place reduction modifier (25%) and were in essence interchangeable from a emission reduction standpoint. In the western regions adoption rates of between 60% and 70% of multiple BMPs on N fertilized crops would need to be achieved to reach the 30% reduction rate. It should be noted that the baseline 2020 adoption rates in Ontario and Quebec (the starting point for the various BMPs) are higher than the western regions, meaning that the percentage change needed on the Prairies are as significant as in eastern regions.

Table 14. 2030 Adoption Rates Required to Achieve a 30% Reduction by Region

	Ontario	**Quebec**	**Wet Prairie East**	**Wet Prairie West**	**Dry Prairie**
BMPs	**2030 Adoption Rates for 30% Reduction**				
Baseline Fertilizer Practice[1]	0%	0%	13%	2%	5%
Enhanced Efficiency Fertilizer	40%	40%	52%	60%	60%
Split Application	60%	60%	35%	38%	35%
Variable rate	100%	100%	60%	70%	70%
Soil Testing	100%	100%	60%	70%	70%

Section Control	100%	100%	60%	70%	70%

[1] Values in the baseline row represent acres of N fertilized crops where neither an EEF or split-application was adopted.

Table 15 below shows the impact of the high adoption rates required to reach 30% fertilizer N_2O emission reductions in each region. The level of fertilizer use decreases because of the higher adoption rates of N saving BMPs, while the total cost of BMPs increases as the BMPs are applied over a larger proportion of the cropped acres. As a result, the net cost per tonne of removal in the western regions rises between \$14 and \$45 per tCO_2e compared to the earlier yield increase scenario. In the eastern regions, the increased adoption rates creates a net benefit of \$13 per tCO_2e in Quebec and \$35 per tCO_2e in Ontario. This net benefit arises because of the greater rates of nitrogen use in those regions particularly by corn. Cost savings on lower total fertilizer volume as BMPs are applied over all acres more than compensate for BMP implementation costs. Keep in mind that to achieve the net benefit Ontario and Quebec growers would need to adopt multiple BMPs; yield and therefore revenue would need to increase; and growers would need to substantially reduce their N rates per unit of crop relying on the BMPs to increase NUE.

One further caveat should be noted here. The model used the average of the 2020-2022 fertilizer price across all years, which by historical standards is high. Essentially, farmers would wholly or partly recover the cost of BMP adoption by using less of an expensive input. If fertilizer price was to fall below 2020-2022 average price, the cost savings from the fertilizer reduction would decrease which would lower the net benefit in the eastern regions (perhaps even negate it altogether) and the cost of the BMPs net of fertilizer savings would increase in all regions.

To achieve these higher rates of adoption an additional investment of \$3.1 billion in BMPs would be required over the 10-year time frame. This calculates out to an increase of \$1.2 billion in investment relative to the more modest adoption rates in the previous yield increase scenario. The net increase in cost over fertilizer savings would be \$391 million. Because this scenario included increased yields and higher adoption rates, the aggregate contribution margin in 2030 increased slightly (\$4.2 to \$4.4 billion) compared to the earlier yield increase scenario. This modest improvement was largely driven by fertilizer cost saving in the eastern regions. Again, the caveat related to the fertilizer price noted above should be applied here as well. BMPs are the most attractive when the cost of implementation is offset by reduced costs or increased yields and revenue. On the cost side, if fertilizer prices fall significantly, the savings and incentive to adopt BMPs will decrease as well, absent any other benefit.

Table 15. Impact of Increased Adoption Rates Required to Achieve a 30% Fertilizer Emission Reduction

	Ontario	**Quebec**	**Wet Prairie East**	**Wet Prairie West**	**Dry Prairie**	**Total**
Summary Results	**Yield increase & adoption rates for 30% reduction**					
% Fertilizer N_2O tCO2e Reduction in 2030 from 2020 baseline	**-30%**	**-30%**	**-30%**	**-30%**	**-30%**	
Nitrogen Change						
Change in lbs per acre of nitrogen in 2030 from 2020 baseline	(1.54)	(3.86)	(2.45)	(5.46)	(4.92)	
Percentage change	-1.8%	-4.8%	-2.4%	-5.0%	-5.4%	
Change in total tonnes of nitrogen in 2030 from 2020 baseline	(4,312)	(4,125)	(9,130)	(62,920)	(38,239)	(118,726)
Cumulative tonnes of nitrogen change	(28,309)	(18,837)	(92,957)	(375,629)	(239,323)	(755,055)

Cost of BMP Implementation ($millions)						
Total BMP cost of implementation in 2030	98	42	101	321	194	756
Total BMP cost of implementation in 2020 baseline	24	10	20	49	32	136
Net cost of implementation (total - baseline)	74	32	80	271	161	618
Total BMP cost net of fertilizer and seed in 2030	(13.3)	(1.6)	19	32	27	63
10 year BMP Costs ($millions)						
10-yr cumulative cost of BMP implementation	636	264	662	1,895	1,180	4,636
10-yr cumulative cost net of baseline cost of BMP implementation	370	158	440	1,340	820	3,127
10-yr cumulative net cost of BMP - less fertilizer and seed cost change	(47.4)	2.9	112	183	140	391
Cost of Fertilizer N_2O tCO_2e Reductions						
10-yr cumulative fertilizer **N_2O** reduction from 2020 baseline (tCO_2e)	(2,083,461)	(1,328,415)	(2,281,871)	(5,814,711)	(3,610,118)	(15,118,576)
Fertilizer **N_2O** Reduction in 2030 from 2020 baseline (tCO_2e)	(429,480)	(292,008)	(388,738)	(1,137,047)	(680,818)	(2,928,092)
Average net cost per tonne for removal in 2030	$(30.97)	$(5.40)	$47.89	$28.14	$ 40.38	$21.59
Average net cost per acre for removal in 2030	$(35.59)	$(12.96)	$45.20	$14.36	$18.83	
Contribution Margin						
Contribution margin per acre 2030	314	202	227	168	174	
Contribution margin per acre 2030 less baseline 2030	60	51	75	85	67	
Contribution margin impact on total acres in 2030 (millions)	369	119	616	2,162	1,143	4,410

Summary of Financial and Emission Reduction Outcomes

In the approach used in this study, all BMPs imposed costs relative to the baseline (for example, premiums for an EEF, or per acre costs for variable rate recommendations) that were wholly or partially compensated for by savings in inputs (reduced N fertilizer rates as well as reduced P, K, S fertilizer and seed volumes for section control) or increases in yield and/or crop price.

In the no yield increase scenario, added costs were not fully compensated at the regional level using reasonable, if somewhat optimistic, increases in adoption rates. The emission reductions estimated from the 2020 baseline reached a substantial 2.5 MtCO2e per year by 2030 but fell short of 30% reduction for the regions and crops included in the model. While inclusion of other crops, additional BMPS, and excluded regions would narrow the gap, the current treatment covers more than 90% of fertilizer N applied and account for more than 95% of baseline N_2O emissions.

The cumulative cost of BMPs implementation from 2020 out to 2030 was estimated at $3.4 billion. This represents the additional investment required by crop producers in aggregate to reach an annual emission reduction of 2.5 $MtCO_2e$ by 2030. These BMP costs when integrated into a reasonably foreseeable future of crop pricing trending downward from the current historic highs and other costs trending upward and adjusted for savings in fertilizer, were a significant contributor to declining contribution margins out to 2030.

Compensation for the cost of BMPs can also occur through increased yields. When yield was increased out to 2030 accompanied by modest increases in fertilizer N, annual emission reduction dropped from 2.5 to 1.6 $MtCO_2e$ in 2030 but contributions margins were $4.2 billion per year higher compared to the no yield increase scenario.

When yield increases were retained and adoption rates raised to levels that would potentially reduce emissions by 30% on a regional basis, emission reduction rose to 2.9 MtCO2e year. While this is short of the 3.5 $MtCO_2e$ target, it represents a 30% reduction in each region for the crops included in the model. Additional savings in fertilizer N as multiple BMPs were applied to an expanded acreage resulted in a slight increase in the contribution margin from $4.2 to $4.4 billion.

The last scenario while most effective at reducing emission from fertilizer N and improving economic returns essentially required adoption of multiple BMPs on all acres of N fertilized crops included in the model. Achieving these very high adoption rates of multiple BMPs by 2030 is simply not feasible. On an actual farm, growers are likely to approach application of multiple BMPs and corresponding cuts in N rate with extreme caution. Adoption of BMPs that require significant capital equipment expenditures such as VR and section control will occur slowly as equipment is turned over. In our yield increase scenarios, increasing yield more than offset the costs of BMPs. In the real world, the costs of BMPs will represent real money spent, while the increased returns from improved yields may not reliably occur.

Program and Policy Considerations

1. The NIR is not a static document and ongoing changes may change the absolute target for emission reductions if the 2020 baseline is recalculated. ECCC and/or AAFC needs to explicitly state the reduction target in kilo tonnes of carbon dioxide equivalents target and update the value with each iteration of the NIR, if the baseline is recalculated.

2. Emission intensities vary regionally, rate optimization approaches that reduce a pound of fertilizer N applied to corn in Quebec would have approximately 4 times the impact on N_2O emissions of an equivalent reduction to canola in Saskatchewan. Source, time, and place BMPs will likely have a significantly larger impact in the regions with higher emission intensity.

3. For BMPs with similar costs across regions, for example conversion to a nitrification inhibitor, costs per tCO_2e reduced will be proportionally lower in regions with higher intensity emissions. Emission intensities will significantly influence which BMPs are cost effective as reduction strategies in a region.
4. Programs and policies in the near term need to focus on BMP adoption in annual cropping systems, in regions with extensive acres, higher per acre N use, and higher emission intensities. Short term priorities should be BMP adoption in the moister regions of the Prairies, Ontario, and Quebec with the dry prairies, British Columbia and the Atlantic Provinces as secondary priorities.
5. The cost of BMP adoption is just one barrier faced by farmers aiming to reduce their nitrous oxide emissions. There are also agronomic, market access, and environmental constraints that must be overcome. Programs and policies must be based on a comprehensive assessment of impacts to avoid unintended consequences that may undercut the economic, social and environmental sustainability of Canadian crop production.
6. Policy and programs need to be built around comprehensive carbon accounting in crop production systems with an aim at reducing carbon emission intensity. Policies and measurement approaches that assign emission sources to crop production without crediting emission sinks unfairly burden an industry that has and continues to be a leader in nature-based solutions.

The economic tool developed as part of this study will be made available and can be used to assess the cost of BMP adoption and emission reduction potential at the regional and farm level on a go forward basis. Regional farm scenarios illustrating the financial impacts and projected emission reductions for various BMPs and combinations of BMPs with rotational and land management strategies will be released as the consultation process continues.

Final Thoughts

Moving crop production from the current state to a future state where the economic sustainability of farms is maintained or enhanced; the carbon intensity of crops is significantly reduced; productivity of the entire cropping and value-added sector is increased; and reductions in GHG emissions from cropping systems are achieved will require a significant effort by the grower community, the upstream and downstream value chain, and governments at both the provincial and federal levels.

Further grower education, access to capital, clear signals from markets and government, and new tools that can track progress will all be necessary. In-order-to make the transition, farmers will have to master new technology or have access to people and services that can manage the technology for them. The agricultural service industry will need to invest further in their systems, people and products and create a stronger link between production decisions, economic returns for the farmer and GHG emissions. Governments need to set clear goals and processes for sorting out conflicting government policies. Since they are the scorekeeper, they will need to create transparency around tools such as the NIR. They will also need to create a clear process for inclusion of new N management BMPs within their policy frameworks as under current programs such as OFCAF inclusion or exclusion appear to be arbitrary if not capricious. Program delivery needs to improve dramatically, the Government of Canada has declared a climate emergency and set ambitious goals for reductions but can’t deliver programs in a timely manner.

In the authors’ view, the focus on absolute reductions from a single source, N fertilizer is misguided and a 30% absolute reduction by 2030 is an overly ambitious and unachievable goal. The focus should be on developing a net zero approach that includes cropping system sinks such as carbon sequestration as well as sources such as fertilizer and fuel use. The focus in the short-term to 2030 needs to be on reducing emission intensity per unit of N applied and per unit of crop produced. Furthermore, comprehensive carbon accounting should be used in setting goals and measuring progress in GHG mitigation. On that point, far better data collection systems and estimation processes are required than are currently available through tools like the NIR. While much foundational work has been done by the research community, grower and industry organizations, and government in our opinion a sober second look at the current strategy and how reductions can be achieved without risking the economic sustainability of farms and the crop-based economy is required.

Appendix 1. Supplemental Information on the 2022 NIR and 4R Climate Smart Protocol

20200 NIR

The Government of Canada announced their industry reduction targets for greenhouse gas emissions (GHG) in late 2020. These targets included a 30% absolute reduction in the greenhouse gas nitrous oxide (N_2O) arising from field applications of nitrogen fertilizer by 2030 using 2020 emissions as the baseline. Although the 30% reduction was announced in 2020, it was only with the release of the 2022 National Inventory Report (NIR) that the crops sector could start to put actual numbers in terms of tons of carbon dioxide equivalents (tCO_2e) to the reduction target. The 2022 NIR introduced changes to the calculation of the nitrous oxide emissions from agricultural soils. These changes tended to reduce emissions attributable to fertilizer N per kilogram of N applied. The changes that directly affect the 2020 estimation of nitrous oxide from fertilizer can be summarized as follows:

1. Recalculation of the ecodistrict emission factor (EF_{eco} or EF_base) used to estimate direct nitrous oxide emissions from crop land.
2. Introduction of a scaling factor that reduces direct emissions from fertilizer N applied to perennial crops by 81% on average.
3. Minor changes in the regional coefficients used to calculate fertilizer N volatilization losses.
4. Introduction of the 2019 IPCC emission factors for redeposited volatilized N that differentiate between dry (0.005 kg N2O-N/kg N) and wet regions (0.014 kg N2O-N/kg N).

Overall, the estimated nitrous oxide emissions attributable to fertilizer N application have been reduced by approximately 20% compared to the previous calculation methods. The updated approach for calculating direct nitrous oxide emissions in the 2022 NIR is largely derived from Liang et al. (2020) and replaces the previous method based on Rochette et al. (2008). Without diving too deep, the main result is higher direct emissions per unit of N applied in ecodistricts with wetter climates, landscapes with a greater proportion of depressions, and finer textured soils. Regionally EF_{eco} values increased the most in British Columbia and decreased the most in Prince Edward Island. However, the really significant reductions due to the method change occurred on the Prairies were lower emission factors were applied to high total fertilizer N volumes.

Changes to the NIR will be ongoing. For example, updating the emission factor for leached nitrogen from the IPCC 2006 value (0.0075 kg N_2O/kg N) to the IPCC 2019 value (0.011 kg N_2O/kg N). This which would increase indirect nitrous oxide emissions from leached N by 45%. The NIR 2022 Part 1 suggests that there will also be changes to incorporate the emission reduction potential of BMPs into nitrous oxide estimates within the next three to five years. This would require a significant improvement in farm activity data in-order-to accurately estimate BMP adoption rates as well as developing a methodology to generate appropriate emission factors for individual and combinations of BMPs.

4R Climate Smart Protocol

The 4R Climate Smart Protocol (4R CSP) is derived from the NIR methodology with modification to allow estimation of N_2O emission reductions when 4R nitrogen management BMPs are adopted. It was first developed as the Nitrous Oxide Emission Reduction Protocol (NERP) offset protocol under Alberta's GHG emission reduction regulations. The relevant equations are shown below:

$$N_2O_{Direct\ Fertilizer} = \sum N_{Fertilizer} \times EF_{eco} \times Molar\ Ratio$$

$$N_2O_{Volatilization\ Fertilizer} = \sum N_{Fertilizer} \times F_{Volatilization} \times EF_{VN} \times Molar\ Ratio$$

$$N_2O_{Leached\ Fertilizer} = \sum N_{Fertilizer} \times F_{Leached} \times EF_{LN} \times Molar\ Ratio$$

$$N_2O_{Fertilizer} = \sum (N_2O_{Direct}, N_2O_{Volatilization}, N_2O_{Leached})$$

$$ER_{N2O\ Fertilizer} = N_2O_{Fertilizer} \times Reduction\ Modifier$$

N_2O Direct Fertilizer = Direct N_2O emissions.

$N_{Fertilizer}$ = Mass of N (kg) in fertilizer.

EF_{eco} = Emission factor direct emissions.

$N_2O_{Volatilization}$ = Indirect N_2O emissions from volatilization of fertilizer N.

$F_{Volatilization}$ = Fraction of added fertilizer N that volatilizes following application.

EF_{VN} = Volatilized N emission factor.

$N_2O_{Leached\ Fertilizer}$ = Indirect N_2O emissions from leaching of fertilizer N.

$F_{Leached}$ = Fraction of fertilizer and crop residue N that leaches.

EF_{LN} = Leached N emission factor.

$N_2O_{Fertilizer}$ = Total N_2O emissions attributable to fertilizer.

$ER_{N2O\ Fertilizer}$ = Emission reduction using dynamic baseline method.

Reduction Modifier = Proportion of emissions reduced through adoption of BMPs.

Nitrous oxide emissions were calculated for each crop in a region after adjusting fertilizer N rate for rate reductions attributable to BMP adoption levels and a weighted reduction modifier based on BMP adoption levels. The N_2O emissions calculated for each crop year were summed and compared to the 2020 estimate with the difference representing the emission reduction attributable to BMP adoption.

Fertilizer Canada and Canola Council of Canada have developed an economic tool to assess the cost of BMP adoption and emission reduction potential at the regional and farm level. Regional scenarios illustrating the net cost and projected emission reductions for various BMPs and combinations of BMPs will be released as the consultation process continues.

References Appendix 1

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Appendix 2. Summary of Financial and Emission Analysis for Three Reduction Scenarios

	Ontario			Quebec			Wet Prairie East			Wet Prairie West			Dry Prairie			Total		
Summary Results	No Yield Increase	Yield increase	Yield increase & adoption rates for 30% reduction	No Yield Increase	Yield increase	Yield increase & adoption rates for 30% reduction	No Yield Increase	Yield increase	Yield increase & adoption rates for 30% reduction	No Yield Increase	Yield increase	Yield increase & adoption rates for 30% reduction	No Yield Increase	Yield increase	Yield increase & adoption rates for 30% reduction	No Yield Increase	Yield increase	Yield increase & adoption rates for 30% reduction
% Fertilizer N2O tCO2e Reduction in 2030 from 2020 baseline	-23%	-11%	-30%	-22%	-13%	-30%	-31%	-23%	-30%	-25%	-17%	-30%	-26%	-19%	-30%			
Nitrogen Change																		
Change in lbs per acre of nitrogen in 2030 from 2020 baseline	(5.37)	6.38	(1.54)	(5.75)	3.20	(3.86)	(8.99)	1.64	(2.45)	(10.25)	1.60	(5.46)	(8.40)	0.27	(4.92)			
Percentage change	-6.4%	7.6%	-1.8%	-7.1%	3.9%	-4.8%	-8.7%	1.6%	-2.4%	-9.3%	1.5%	-5.0%	-9.3%	0.3%	-5.4%			
Change in total tonnes of nitrogen in 2030 from 2020 baseline	(14,993)	17,833	(4,312)	(6,142)	3,411	(4,125)	(33,552)	6,116	(9,130)	(118,111)	18,456	(62,920)	(65,329)	2,121	(38,239)	(238,128)	47,936	(118,726)
Cumulative tonnes of nitrogen change	(75,007)	72,036	(28,309)	(30,521)	12,567	(18,837)	(194,428)	(16,091)	(92,957)	(684,496)	(70,832)	(375,629)	(378,346)	(75,193)	(239,323)	(1,362,798)	(77,511)	(755,055)
Cost of BMP Implementation ($millions)																		
Total BMP cost of implementation in 2030	$ 56	$ 56	$ 98	$ 24	$ 24	$ 42	$ 75	$ 75	$ 101	$ 208	$ 208	$ 321	$ 131	$ 131	$ 194	$ 495	$ 495	$ 756
Total BMP cost of implementation in 2020 baseline	$ 24	$ 24	$ 24	$ 10	$ 10	$ 10	$ 20	$ 20	$ 20	$ 49	$ 49	$ 49	$ 32	$ 32	$ 32	$ 136	$ 136	$ 136
Net cost of implementation (total - baseline)	$ 32	$ 32	$ 74	$ 14	$ 14	$ 32	$ 55	$ 55	$ 80	$ 157	$ 157	$ 271	$ 98	$ 98	$ 161	$ 357	$ 357	$ 618
Total BMP cost net of fertilizer and seed in 2030	$ 1.3	$ 9.3	$ (13.3)	$ 4	$ 6	$ (2)	$ 20	$ 31	$ 19	$ 48	$ 85	$ 32	$ 36	$ 53	$ 27	$ 109	$ 184	$ 63
10 year BMP Costs ($millions)																		
10 yr cumulative cost of BMP implementation	$ 427	$ 427	$ 636	$ 184	$ 184	$ 264	$ 521	$ 521	$ 662	$ 1,401	$ 1,401	$ 1,895	$ 888	$ 888	$ 1,180	$ 3,420	$ 3,420	$ 4,636
10 yr cumulative cost net of baseline cost of BMP implementation	$ 161	$ 161	$ 370	$ 78	$ 78	$ 158	$ 298	$ 298	$ 440	$ 846	$ 846	$ 1,340	$ 528	$ 528	$ 820	$ 1,912	$ 1,912	$ 3,127
10 yr cumulative net cost of BMP - less fertilizer and seed cost change	$ 2.9	$ 68.2	$ (47.4)	$ 23	$ 39	$ 3	$ 139	$ 228	$ 112	$ 355	$ 650	$ 183	$ 245	$ 387	$ 140	$ 765	$ 1,372	$ 391
Cost of Fertilizer N2O tCO2e Reductions																		
10 yr cumulative fertilizer N_2O tCO_2e reduction from 2020 baseline (tonnes)	(1,580,889)	(700,988)	(2,083,461)	(1,074,812)	(647,587)	(1,328,415)	(2,388,051)	(1,798,596)	(2,281,871)	(5,830,333)	(4,423,752)	(5,814,711)	(3,555,585)	(2,788,876)	(3,610,118)	(14,429,671)	(10,359,799)	(15,118,576)
Fertilizer N_2O tCO_2e Reduction in 2030 from 2020 baseline (tonnes)	(311,781)	(124,994)	(429,480)	(213,622)	(123,747)	(292,008)	(400,621)	(274,936)	(388,738)	(978,010)	(677,937)	(1,137,047)	(596,880)	(433,353)	(680,818)	(2,500,914)	(1,634,966)	(2,928,092)
Average net cost per tonne for removal in 2030	$ 4.05	$ 74.34	$ (30.97)	$ 17.42	$ 46.87	$ (5.40)	$ 50.56	$ 113.34	$ 47.89	$ 49.50	$ 124.96	$ 28.14	$ 59.62	$ 122.61	$ 40.38	$ 43.68	$ 112.60	$ 21.59
Average net cost per acre for removal in 2030	$ 5.00	$ 101.65	$ (35.59)	$ 47.59	$ 137.09	$ (12.96)	$ 46.51	$ 112.35	$ 45.20	$ 25.54	$ 70.45	$ 14.36	$ 28.10	$ 63.17	$ 18.83			
Contribution Margin																		
Contribution margin per acre 2030	$ 253	$ 310	$ 314	$ 150	$ 199	$ 202	$ 150	$ 226	$ 227	$ 81	$ 166	$ 168	$ 106	$ 173	$ 174			
Contribution margin per acre 2030 less baseline 2030	$ (0)	$ 56	$ 60	$ (2)	$ 48	$ 51	$ (2)	$ 73	$ 75	$ (2)	$ 83	$ 85	$ (2)	$ 65	$ 67			
Contribution margin impact on total acres in 2030 (millions)	$ (1)	$ 347	$ 369	$ (4)	$ 112	$ 119	$ (20)	$ 604	$ 616	$ (48)	$ 2,109	$ 2,162	$ (36)	$ 1,117	$ 1,143	$ (109)	$ 4,289	$ 4,410
Per Acre Costs																		
BMP costs per acre in 2030	$ 9.12	$ 9.12	$ 15.88	$ 10.24	$ 10.24	$ 17.82	$ 9.15	$ 9.15	$ 12.26	$ 8.19	$ 8.19	$ 12.64	$ 7.64	$ 7.64	$ 11.29			
Net BMP costs per acre in 2030 (2030 minus 2020 baseline)	$ 5.20	$ 5.20	$ 11.96	$ 6.13	$ 6.13	$ 13.70	$ 6.65	$ 6.65	$ 9.76	$ 6.20	$ 6.20	$ 10.65	$ 5.72	$ 5.72	$ 9.37			
BMP costs net of reductions in fertilizer and seed cost in 2030	$ 0.21	$ 1.51	$ (2.16)	$ 1.58	$ 2.46	$ (0.67)	$ 2.46	$ 3.79	$ 2.26	$ 1.90	$ 3.33	$ 1.26	$ 2.08	$ 3.10	$ 1.60			

BMPs	2020 Baseline Adoption Rates	2030 Adoption Rates (used for no yield and increased yield)	2030 Adoption Rates for 30% Reduction	2020 Baseline Adoption Rates	2030 Adoption Rates (used for no yield and increased yield)	2030 Adoption Rates for 30% Reduction	2020 Baseline Adoption Rates	2030 Adoption Rates (used for no yield and increased yield)	2030 Adoption Rates for 30% Reduction	2020 Baseline Adoption Rates	2030 Adoption Rates (used for no yield and increased yield)	2030 Adoption Rates for 30% Reduction	2020 Baseline Adoption Rates	2030 Adoption Rates (used for no yield and increased yield)	2030 Adoption Rates for 30% Reduction
Baseline - Urea Fertilizer	51%	2%	0%	51%	2%	0%	90%	24%	13%	90%	24%	2%	90%	24%	5%
Enhanced Efficiency Fertilizer	13%	38%	40%	13%	38%	40%	8%	48%	52%	8%	48%	60%	8%	48%	60%
Split Application	36%	60%	60%	36%	60%	60%	2%	28%	35%	2%	28%	38%	2%	28%	35%
Variable rate	15%	45%	100%	15%	45%	100%	15%	45%	60%	15%	45%	70%	15%	45%	70%
Soil Testing	10%	26%	100%	10%	26%	100%	25%	50%	60%	25%	50%	70%	25%	50%	70%
Section Control	10%	28%	100%	10%	28%	100%	10%	28%	60%	10%	28%	70%	10%	28%	70%

Crops	Acres	Crops	Acres	Crops	Acres	Crops	Acres	Crops	Acres		
Ontario - Corn for grain	2,116,300	Québec - Corn for grain	919,967	Wet Prairie East - Canola	3,315,467	Wet Prairie West - Canola	11,522,867	Dry Prairie - Canola	6,824,500		
Ontario - Soybeans	2,989,967	Québec - Soybeans	910,867	Wet Prairie East - Dry Peas	134,608	Wet Prairie West - Dry Peas	1,823,267	Dry Prairie - Lentils	3,200,267		
Ontario - Wheat, all	1,051,567	Québec - Wheat, all	229,700	Wet Prairie East - Spring Wheat	2,903,850	Wet Prairie West - Spring Wheat	8,345,000	Dry Prairie - Durum Wheat	5,027,783		
		Québec - Oats	169,767	Wet Prairie East - Barley	322,092	Wet Prairie West - Barley	3,721,767	Dry Prairie - Barley	2,090,133		
		Québec - Barley	123,333	Wet Prairie East - Soybeans	1,555,583						
Total	**6,157,833**	**Total**	**2,353,633**	**Total**	**8,231,600**	**Total**	**25,412,900**	**Total**	**17,142,683**	**Total Acres - All Regions**	**59,298,650**

Appendix 3. Adoption Rates for 4R BMPs

The tables below list the adoption rates used in each region for the initial no yield and yield increase scenarios. The adoption rates required to reach 30% reduction in each region are reported in the main text. The 2020 baseline adoptions for the various practices were derived from the Fertilizer Use Surveys tempered with professional judgement. For example, on the Prairies growers with section control will be using it on their pulse crops as well as on their N fertilized crops to realize the savings in seed and fertilizer. They are less likely to use variable rate on their pulses than on their N fertilized crops due to the per acre cost of developing annual VR fertilizer prescriptions. We have reduced the adoption of VR on pulse crops and soybeans accordingly.

Ontario BMP Adoption Rates

Ontario - Corn for grain

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	51%	51%	51%	45%	39%	33%	25%	19%	13%	8%	2%
Enhanced Efficiency Fertilizer	13%	13%	13%	16%	19%	22%	27%	30%	33%	35%	38%
Split Application	36%	36%	36%	39%	42%	45%	48%	51%	54%	57%	60%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Ontario - Soybeans

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Enhanced Efficiency Fertilizer	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Split Application	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable rate	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%	30%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Ontario - Wheat, all

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	80%	80%	80%	75%	70%	65%	60%	60%	60%	60%	60%
Enhanced Efficiency Fertilizer	20%	20%	20%	25%	30%	35%	40%	40%	40%	40%	40%
Split Application	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable rate	6%	6%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Quebec BMP Adoption Rates

Québec - Corn for grain

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	51%	51%	51%	45%	39%	33%	25%	19%	13%	8%	2%
Enhanced Efficiency Fertilizer	13%	13%	13%	16%	19%	22%	27%	30%	33%	35%	38%

Split Application	36%	36%	36%	39%	42%	45%	48%	51%	54%	57%	60%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Québec - Soybeans

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Enhanced Efficiency Fertilizer	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Split Application	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable rate	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%	30%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Québec - Wheat, all

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	82%	82%	82%	77%	72%	67%	61%	58%	55%	53%	50%
Enhanced Efficiency Fertilizer	13%	13%	13%	16%	19%	22%	27%	30%	33%	35%	38%
Split Application	5%	5%	5%	7%	9%	11%	12%	12%	12%	12%	12%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Québec - Oats

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	90%	85%	81%	76%	71%	68%	68%	68%	68%	68%
Enhanced Efficiency Fertilizer	5%	5%	10%	12%	15%	18%	20%	20%	20%	20%	20%
Split Application	5%	5%	5%	7%	9%	11%	12%	12%	12%	12%	12%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Québec - Barley

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	90%	85%	81%	76%	71%	68%	68%	68%	68%	68%
Enhanced Efficiency Fertilizer	5%	5%	10%	12%	15%	18%	20%	20%	20%	20%	20%
Split Application	5%	5%	5%	7%	9%	11%	12%	12%	12%	12%	12%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	10%	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Dry Prairie BMP Adoption Rates

Dry Prairie - Canola

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Dry Prairie - Lentils

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Enhanced Efficiency Fertilizer	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Split Application	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable rate	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Dry Prairie - Durum Wheat

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Dry Prairie - Barley

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie East BMP Adoption Rates

Wet Prairie East - Canola

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%

Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie East - Dry Peas

Scenario	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Baseline	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Enhanced Efficiency Fertilizer	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Split Application	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable rate	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie East - Spring Wheat

Scenario	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie East - Barley

Scenario	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie East - Soybeans

Scenario	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Baseline	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Enhanced Efficiency Fertilizer	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Split Application	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable rate	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie West BMP Adoption Rates

Wet Prairie West - Canola

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie West - Dry Peas

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Enhanced Efficiency Fertilizer	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Split Application	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Variable rate	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie West - Spring Wheat

Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

Wet Prairie West - Barley

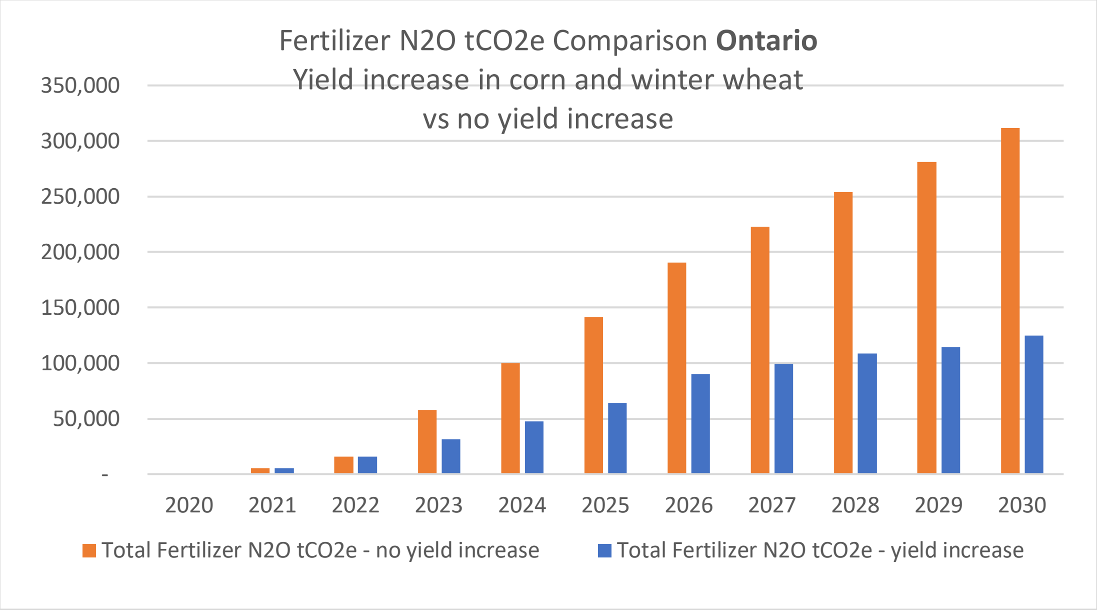
Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Baseline	90%	85%	80%	72%	62%	52%	42%	35%	28%	26%	24%
Enhanced Efficiency Fertilizer	8%	13%	18%	23%	28%	33%	38%	43%	48%	48%	48%
Split Application	2%	2%	2%	5%	10%	15%	20%	22%	24%	26%	28%
Variable rate	15%	18%	21%	24%	27%	30%	33%	36%	39%	42%	45%
Soil Testing	25%	25%	30%	35%	40%	45%	50%	50%	50%	50%	50%
Section Control	10%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%

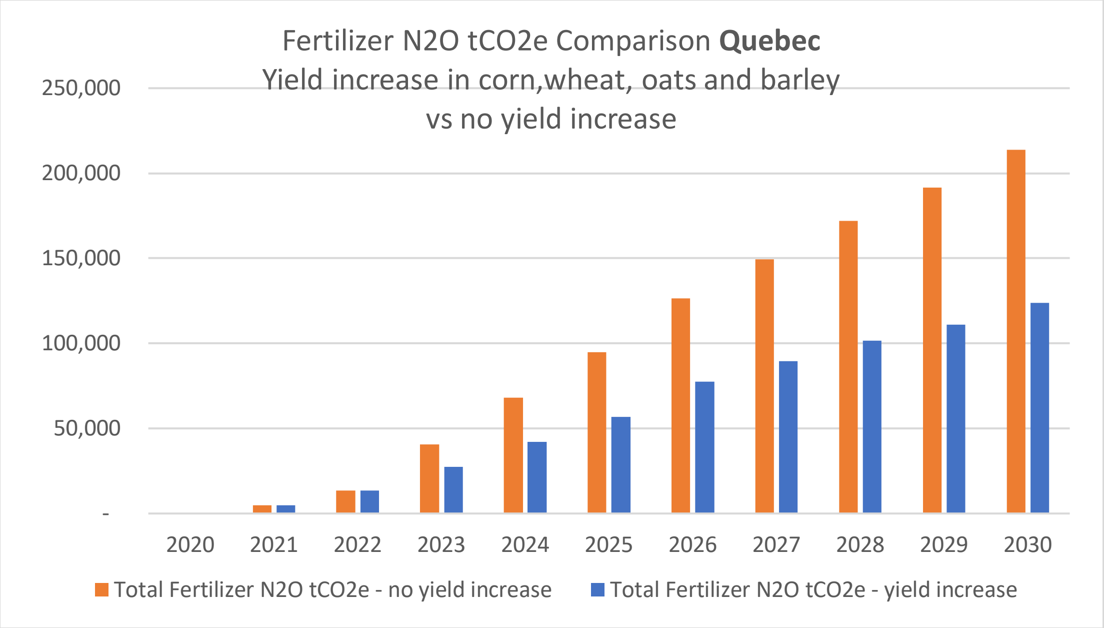
Appendix 4. Summary of Increased Yield and Nitrogen application Rates by Region

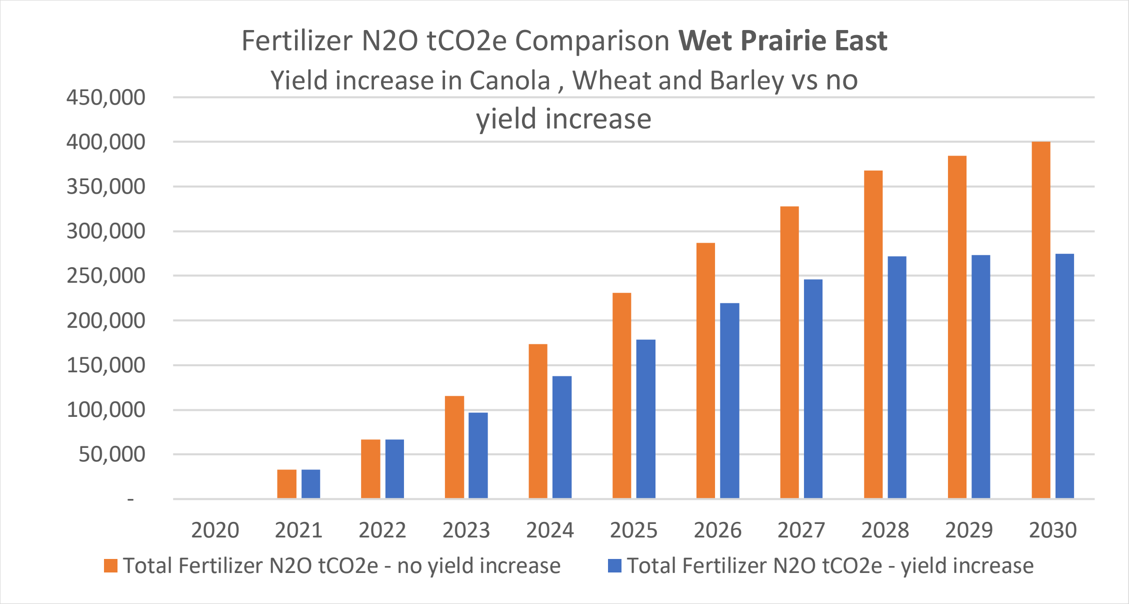
	Ontario		Quebec	
Summary Results	**No Yield Increase**	**With Yield increase**	**No Yield Increase**	**With Yield increase**
% Fertilizer N_2O tCO_2e Reduction in 2030 from 2020 baseline	**-23%**	**-11%**	**-22%**	**-13%**
Nitrogen Change				
Change in lbs per acre of nitrogen in 2030 from 2020 baseline	(5.37)	6.38	(5.75)	3.20
Percentage change	-6.4%	7.6%	-7.1%	3.9%
Change in total tonnes of nitrogen in 2030 from 2020 baseline	(14,993)	17,833	(6,142)	3,411
Cumulative tonnes of nitrogen change	(75,007)	72,036	(30,521)	12,567
Cost of BMP Implementation ($millions)				
Total BMP cost of implementation in 2030	56	56	24	24
Total BMP cost of implementation in 2020 baseline	24	24	10	10
Net cost of implementation (total - baseline)	32	32	14	14
Total BMP cost net of fertilizer and seed in 2030	1.3	9.3	3.7	5.8
10 year BMP Costs ($millions)				
10-yr cumulative cost of BMP implementation	427	427	184	184
10-yr cumulative cost net of baseline cost of BMP implementation	161	161	78	78
10-yr cumulative net cost of BMP - less fertilizer and seed cost change	2.9	68.2	22.5	39.4
Cost of Fertilizer N_2O tCO_2e Reductions				
10-yr cumulative fertilizer **N_2O** tCO_2e reduction from 2020 baseline (tonnes)	(1,580,889)	(700,988)	(1,074,812)	(647,587)
Fertilizer **N_2O** tCO_2e Reduction in 2030 from 2020 baseline (tonnes)	(311,781)	(124,994)	(213,622)	(123,747)
Average net cost per tonne for removal in 2030 ($)	$ 4.05	$ 74	$ 17	$ 47
Average net cost per acre for removal in 2030 ($)	$ 5.00	$ 102	$ 48	$ 137
Contribution Margin ($ millions)				
Contribution margin per acre 2030	253	310	150	199
Contribution margin per acre 2030 less baseline 2030	(0.2)	56	(1.6)	48
Contribution margin impact on total acres in 2030 (millions)	(1.3)	347	(3.7)	112

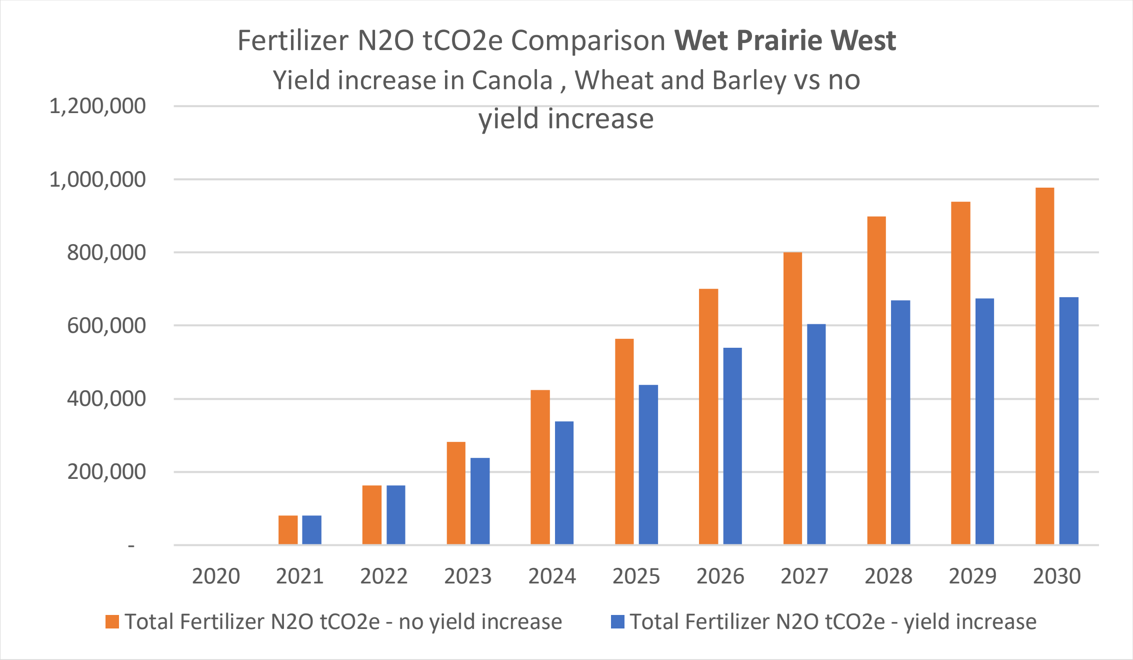
	Wet Prairie East		Wet Prairie West		Dry Prairie	
Summary Results	**No Yield Increase**	**With Yield increase**	**No Yield Increase**	**With Yield increase**	**No Yield Increase**	**With Yield increase**
% Fertilizer N_2O tCO_2e Reduction in 2030 from 2020 baseline	**-31%**	**-23%**	**-25%**	**-17%**	**-26%**	**-19%**
Nitrogen Change						
Change in lbs per acre of nitrogen in 2030 from 2020 baseline	(8.99)	1.64	(10.25)	1.60	(8.40)	0.27
Percentage change	-8.7%	1.6%	-9.3%	1.5%	-9.3%	0.3%
Change in total tonnes of nitrogen in 2030 from 2020 baseline	(33,552)	6,116	(118,111)	18,456	(65,329)	2,121
Cumulative tonnes of nitrogen change	(194,428)	(16,091)	(684,496)	(70,832)	(378,346)	(75,193)
Cost of BMP Implementation ($millions)						
Total BMP cost of implementation in 2030	75	75	208	208	131	131
Total BMP cost of implementation in 2020 baseline	20	20	49	49	32	32
Net cost of implementation (total - baseline)	55	55	157	157	98	98
Total BMP cost net of fertilizer and seed in 2030	20	31	48	85	36	53
10 year BMP Costs ($millions)						
10-yr cumulative cost of BMP implementation	521	521	1,401	1,401	888	888
10-yr cumulative cost net of baseline cost of BMP implementation	298	298	846	846	528	528
10-yr cumulative net cost of BMP - less fertilizer and seed cost change	139	228	355	650	245	387
Cost of Fertilizer N_2O tCO_2e Reductions						
10-yr cumulative fertilizer **N_2O** tCO_2e reduction from 2020 baseline (tonnes)	(2,388,051)	(1,798,596)	(5,830,333)	(4,423,752)	(3,555,585)	(2,788,876)
Fertilizer **N_2O** tCO_2e Reduction in 2030 from 2020 baseline (tonnes)	(400,621)	(274,936)	(978,010)	(677,937)	(596,880)	(433,353)
Average net cost per tonne for removal in 2030	51	113	49	125	60	123
Average net cost per acre for removal in 2030	47	112	26	70	28	63
Contribution Margin ($ millions)						
Contribution margin per acre 2030	150	226	81	166	106	173
Contribution margin per acre 2030 less baseline 2030	(2.5)	73	(1.9)	83	(2)	65
Contribution margin impact on total acres in 2030 (millions)	(20)	604	(48)	2,109	(36)	1,117

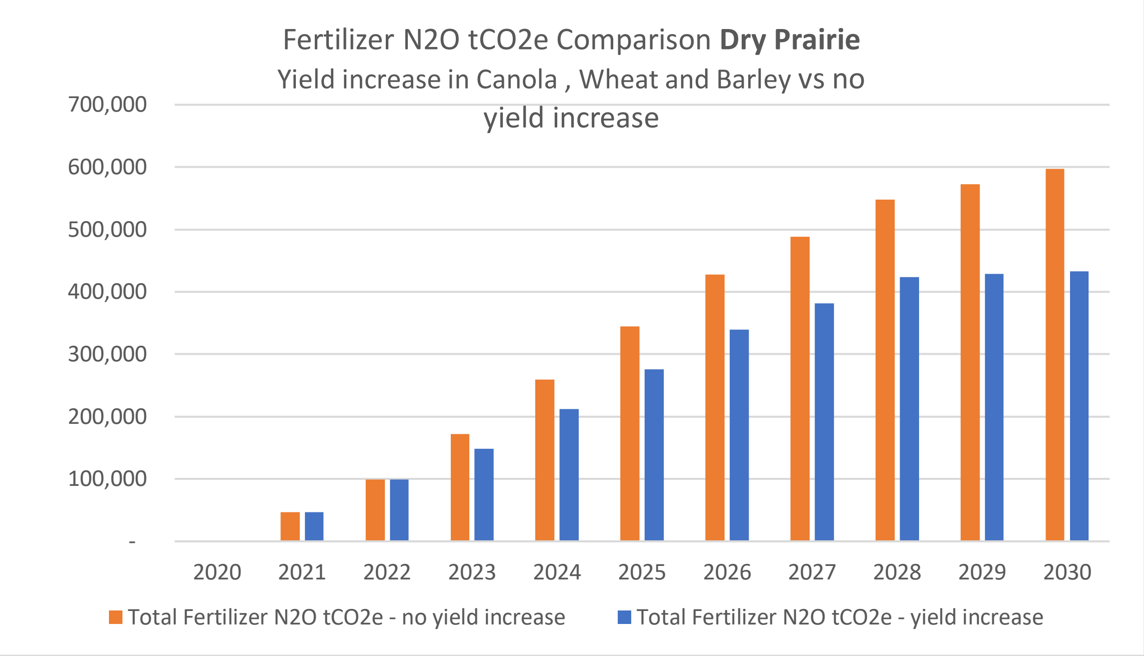
Appendix 5. Regional Fertilizer Emission Reduction No Yield Increase Compared to Yield and Nitrogen Rate Increase.






Fertilizer N2O tCO2e Comparison **Wet Prairie East**
Yield increase in Canola , Wheat and Barley vs no yield increase
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
-
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Total Fertilizer N2O tCO2e - no yield increase
Total Fertilizer N2O tCO2e - yield increase


Fertilizer N2O tCO2e Comparison **Wet Prairie West**
Yield increase in Canola , Wheat and Barley vs no yield increase
1,200,000
1,000,000
800,000
600,000
400,000
200,000
-
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Total Fertilizer N2O tCO2e - no yield increase
Total Fertilizer N2O tCO2e - yield increase


Fertilizer N2O tCO2e Comparison **Dry Prairie**
Yield increase in Canola , Wheat and Barley vs no yield increase
700,000
600,000
500,000
400,000
300,000
200,000
100,000
-
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
Total Fertilizer N2O tCO2e - no yield increase
Total Fertilizer N2O tCO2e - yield increase