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Abstract

A better understanding of the additional costs and potential benefits to producers is needed to meet Canada's fertilizer-based emission reduction target through policies that incentivize on-farm EENF adoption. This research conducts a partial cost-benefit analysis for dryland wheat production in Alberta and EENF use. The research uses a modified version of Canada's National Inventory Report Methodology to estimate direct fertilizer based N_2O emissions. Monte Carlo simulation is used to estimate field-level emissions using a combination of township-level weather and risk zone-level production data. The costs and benefits of EENF adoption to producers were evaluated by estimating potential changes in net revenue, under a business-as-usual scenario and when carbon offsets are provided at a value of $50 and $170 per tonne of CO2eq.

While there a high degree of spatial variability is reflected in our results, the research indicated generally low base emissions across the province with approximately 90 percent of the simulated field level observations below 1.0 kg N_2O emissions per hectare. Low per hectare average emissions will pose a major challenge to the development of an effective carbon offset program for N_2O reductions, due to limited potential revenue generation relative to the cost of adoption. Estimated change in net revenue was highly dependent on the production risk zone and EENF product type used, suggesting limited effectiveness of a one-size-fits-all policy.

Keywords: Enhanced Efficiency Nitrogen Fertilizer, Carbon Offsets, Cost Benefit Analysis, Monte Carlo Simulation

Contents

Policy Recommendations

- Research specific to Alberta on the effectiveness of enhanced efficiency fertilizers (EENFs) in dryland production systems should be prioritized, as the current body of research predominantly focuses centers on fertilizer application in production systems in Ontario and the United States corn belt. Increasing funding and extension to conduct trials in Alberta will fill this research gap and tangibly improve understanding impacts of EENF application, including the financial benefits associated with adoption.
- Ensuring carbon credit protocols and programs are specific to actions measurable at the on-farm level and only paid after emissions have been offset will facilitate verification. This is especially critical in the revision and development of offset protocols to reduce complexity and increase transparency and understanding by linking the adoption of specific activities and measures with carbon credits.
- The development of a rebate program based on the sales of EENFs through retailers of crop inputs is an effective method to eliminate the role of aggregators. Crop input retailers should apply for rebates based on sales of EENFs; payouts from these rebates should result in reduced EENFs consumer prices, further driving uptake.

Introduction

In 2020, greenhouse gas (GHG) emissions in Canada fell to 672 mt CO_2 eq, the largest single year decrease since the National Inventory Report began, and the first year of emission reductions since 2016, the year the Paris Agreement was ratified in Canada (Environment and Climate Change Canada, 2022c). At 10 percent, emissions from the agricultural sectors comprise a small share of total (GHG) emissions, emissions increased from 67 in 2019 to 69 Mt in 2020, driven primarily by increased emissions from crop production, 19 to 21 Mt CO_2eq (Environment and Climate Change Canada, 2022c). Crop production-based emissions have increased by 75 percent since 2005 and was the main contributor to emission growth for the agricultural sector. This growth has been principally attributed to increased nitrogen fertilizer use, which has increased by 89 percent since 2005 (Environment and Climate Change Canada, 2022a), and a result of changing crop mix and intensification of production in the Canadian prairies. Emissions from fertilizer use increased by 75 and 80 percent since 2005 in Alberta and Saskatchewan, representing the most striking growth in Canada (Environment and Climate Change Canada, 2022c).

The Government of Canada introduced *A Healthy Environment and a Healthy Economy* in December 2020, which outlined steps needed to meet Canada's commitments under the Paris Agreement (Environment and Climate Change Canada, 2020). The plan included a proposal for Canada's first national emission target for the agricultural sector, which sought to reduce fertilizer-based emissions by 30 percent of 2020 levels by 2030. Details on the proposed target were provided in a discussion paper from Agriculture and Agrifood Canada (AAFC) published in February of 2022. To meet the target, the document highlighted 11 near-term best management practices (BMPs) that, if universally adopted, could reach, and surpass the proposed target (Agriculture and Agri-Food Canada, 2022). The BMPs were primarily focused on improving fertilizer management through increased adoption rates of 4R nutrient stewardship[1], but also included practices such no-till, diversification of crop rotation, and increased use of cover crops. If all practices were to be fully adopted, AAFC estimated emissions could be reduced by 4.77 Mt CO_2 eq, surpassing the 3.77 Mt reduction target. The surplus reduction potential suggests that the full adoption of proposed BMPs may not be needed

[1] 4R Nutrient Stewardship refers to the “Right Source, Right Rate, Right Time, Right Place®” in fertilizer use.

to meet the emission target. Yet, the near-universal adoption of enhanced efficiency nitrogen fertilizers (EENFs) is essential to meet the proposed target. Alone, universal adoption of EENFs would account for 62 percent of the emission target, making it impossible to achieve the target without EENFs playing a central role in N_2O emission reduction pathways.

Enhanced efficiency nitrogen fertilizers protect against nitrogen loss through N_2O emissions by increasing the duration in which nitrogen is available for uptake by crops (Ferguson et al., 2019). There are two general types of EENFs: controlled release nitrogen (CRN), and stabilized nitrogen. First, CRN, uses a physical coating to protect against nitrogen loss (Nutrien, n.d.). Nitrogen is released slowly throughout the growing season as the coating breaks down. Stabilized nitrogen can be classified in three categories: nitrification inhibitor (NI), urea inhibitor (UI), or when combined, double inhibitor (DI). These products protect against nitrogen loss using chemical inhibitors to reduce hydrolysis (UI) or nitrification (NI) rates (Ferguson et al., 2019). AAFC (2022) estimated that EENF use could reduce emission by 15 to 35 percent compared to conventional fertilizers. While not discussed in the AAFC document, as EENFs help ensure that nitrogen is available at the right time, significant yield increases have been observed across multiply studies (Young et al., 2021). Despite the potential for a win-win scenario and being commercially available for over two decades, EENF on-farm adoption is low, with only 20 percent of wheat acres in Western Canada utilizing the products (Fertilizer Canada, 2021).

The development of carbon offsets for the agricultural sector is often touted as an effective way to reduce emissions through the incentivized adoption of best management practices (BMP) (Alberta Agriculture Forestry and Rural Economic Development, 2011). Adoption is incentivized by creating a market for producers to sell their quantified emission reduction from the BMP adoption to large emitters under cap-and-trade systems. Alberta's Technology Innovation and Emissions Reduction (TIER) Regulation has developed several offset protocols for the agricultural sector. The Nitrous Oxide Emission Reduction Protocol (NERP) was developed to generate offsets from improved fertilizer management and require the adoption of a suite of BMPs, including the adoption of EENFs (Government of Alberta, 2015). While in theory, NERP is well designed to help meet the 2030 fertilizer-based emission reduction target, there has been extremely limited participation in the protocol since its launch (van Wyngaarden, 2022).

Better understanding of the additional cost and potential benefits to producers is essential to develop policies to help incentivize EENF adoption. This consideration was noticeably absent in the AAFC discussion document, highlighting N_2O emission reduction potential without discussing cost or improved yield performance. To that extent, our objective is to assess the additional costs and benefit of EENF adoption for dryland wheat production in Alberta. The study uses a modified version of Canada's National Inventory Report Methodology to estimate direct fertilizer based N_2O emissions. Monte Carlo simulation is used to estimate field-level emissions using a combination of township-level weather and risk zone-level production data. The costs and benefits of adoption to producers were evaluated by estimating potential changes in revenue with no additional incentives, and when carbon offsets are valued at \$50 and \$170 per tonne of CO_2eq.

While there is a high degree of spatial variability, our research indicates emissions across the province are generally low with approximately 90 percent of the simulated field level observations emitting less than 1.0 kg N_2O per ha. At the provincial level, the mean and median per hectare emission estimates were found to be 0.615 kg and 0.46 kg N_2O respectively. Low per hectare average emissions will pose a major challenge to the development of an effective carbon offset program for N_2O reduction, due to limited revenue generation potential relative to the cost of adoption. For both controlled CRF and DI products, the majority of observations were found to be negative even when an offset of \$170 per tonne of CO_2eq was provided. Conversely, both NI and UI products were effective at increasing net revenue even when no offset was provided. Except for double inhibitors, the introduction of carbon offsets was not found to significantly increase the percentage of positive results suggesting that alternative strategies would be required to promote their adoption.

Data and Methodology

The project uses generated field-level observations to assess the mitigation potential and changes in revenue associated with EENF adoption across several scenarios within each township. Within each of the 3,555 townships, 10,000 field-level observations were generated using Monte Carlo simulation. Table 1 provides a summary of the variables used in this analysis, assumptions made about the distribution of the variables, and data sources. The simulated dataset was then used to estimate emissions following Canada's Tier-2 Country Specific (Can2) methodology for direct N_2O emissions from agricultural soils introduced in the 2022 National

Inventory Report (NIR). In its simplest form, direct fertilizer-based N_2O emissions are estimated by multiplying total fertilizer use by a conversion rate known as an emission factor (IPCC, 2019). The complexity of the methodology is generally based on how the emission factor is estimated. Tier 1 approaches, used by 79 percent of countries reporting annual emissions to the UNFCCC (Bourassa & Vinco, 2022), use a default value of 1 percent (0.01 kg N_2O-N kg N^{-1}) for all direct N_2O sources as of 2021 (IPCC, 2019). Country-specific methodologies generally differentiate emission factors by a few characteristics with a set of emission factors for each outcome. For example, Russia and the Netherlands have different emission factors for different soil types (Romanovskaya et al., 2021; Ruyssenaars et al., 2021). Japan differentiates emission factors by production system and if an inhibitor is used (Ministry of the Environment & National Institute for Environmental Studies, 2021). Only three countries, Canada, the United Kingdom, and the United States, have developed methodologies with estimates based on localized environmental and production characteristics (Brown et al., 2021; Environment and Climate Change Canada, 2022b; Environmental Protection Agency, 2021). The Can2 model uses a combination of long-term average growing season weather, topographical, and soil data to estimate an emission factor, which can then be modified by ratio factors to account for different farming practices (Environment and Climate Change Canada, 2022b). The emission factor is then multiplied by the nitrogen application rate, resulting in an emission estimate. This approach is flexible, allowing the incorporation of new farming practices with the development of new ratio factors, and is scalable based on data availability.

Annual N_2O Emissions

The Modified Can2 model estimates annual N_2O emissions per field (hectare) using Equation 1, where $N_2O_{f,t,z,s}$ is annual N_2O emissions for field f, in township t, in risk zone z, and nitrogen source. Annual emissions are estimated as a function of the fertilizer application rate $\left(N_{Fert,f,z,}\right)$, the base emission factor $\left(EF_{Base,f,t}\right)$, the ratio factor for the nitrogen source $\left(RF_{NS,s}\right)$, and the factors for converting growing season emissions to annual emissions $\left(\frac{1}{0.634}\right)$ and N_2O-N to N_2O $\left(\frac{44}{28}\right)$ (Environment and Climate Change Canada, 2022b).

$$N_2O_{f,t,z,s} = \left(\left[N_{Fert,f,z} \times \left(\frac{1}{0.634} \times EF_{Base,f,t} \times RF_{NS,f,s}\right)\right] \times \frac{44}{28}\right) \quad (1)$$

Nitrogen Application Rate

This research assumes that farmers select a nitrogen application rate to meet a specific target yield. The target is based on historical output for the risk zone. Equation 2 is used to estimate $N_{Fert,f,z}$ and is a function of the target yield $(Yield_{f,z})$. Equation 2 relies on the assumption that production is occurring in mineral soils with a soil organic matter content less than or equal to 5 percent, the soil is adequately drained, and the farmer does not account for residual nitrogen within the soil (Lentz et al., 2018).

$$N_{Fert,f,z} = 1.121 \times \left(40 + \left[1.75 \times \left(Yield_{f,z} - 50\right)\right]\right) \quad (2)$$

Data on yield used to calculate $N_{Fert,f,z}$ was manually collected from annual publications of crop insurance yield data by Agriculture Financial Services Corporation (AFSC) and Alberta Farmer (AF) (2015, 2016, 2017, 2018, 2019, 2020, 2021). The data covered seven years, 2020-2014, and provided yield averages at the risk zone level. $Yield_{f,z}$ values were generated by randomly selecting from a uniform distribution where the upper and lower limits were the maximum and mean yield values over the 7 years. Figure 1 provides a reference map of the approximate boundaries of risk zones within the province. Figure 2 provides a range plot for the distribution of yields over the 7-year period by risk zone.

Base Emission Factor

The base emission factor is the weighted average of emission factors for precipitation $(EF_{CT,f,t})$ and potential evapotranspiration $(EF_{CT,P=PE,f,t})$ multiplied by a ratio factor for the texture of the soil $(RF_{TX,i})$, see Equation 3 (Environment and Climate Change Canada, 2022b). The weights for $EF_{CT,f,t}$ and $EF_{CT,P=PE,f,t}$ are based on the fraction of low-lying ground within the field (FR_{Topo}), which is assumed to be partially saturated throughout the growing season resulting in higher emissions. Within the Can2 model used in the National Inventory Report, RF_{TX} is based on the weighted average of soil textures within the eco-district with values of 2.55, 1, and 0.49, corresponding to fine, medium, and coarse soils (Environment and Climate Change Canada, 2022b).

$$EF_{Base,f,t} = \left[EF_{CT,P=PE,f,t} \times FR_{Topo,f} + EF_{CT,f,t} \times \left(1 - FR_{Topo,f}\right)\right] \times RF_{TX,f} \quad (3)$$

The emission factors $EF_{CT,f,t}$ and $EF_{CT,P=PE,f,t}$ are estimated using Equation 4 and Equation 5. The difference between the two equations is that Equation 4 estimates the emission factor using precipitation $\left(P_{n,f,t}\right)$ while Equation 5 uses potential evapotranspiration $\left(PE_{n,f,t}\right)$.

$$EF_{CT,f,t} = e^{\left((0.00558 \times P_{f,t}) - 7.701\right)} \tag{4}$$

$$EF_{CT,P=PE,f,t} = e^{\left((0.00558 \times PE_{f,t}) - 7.701\right)} \tag{5}$$

Canada's NIR utilizes a 30-year growing season average for precipitation and potential evapotranspiration. The NIR growing season is defined as the period between May 1st and October 31st using data covering the period between 1971 and 2000 (Environment and Climate Change Canada, 2022b). The definition of the growing season was kept in this analysis to remain consistent with the NIR. However, the years covered were updated for the period of 1992 to 2021. The granularity of the data used was increased from eco-district level to townships[2]. Daily interpolated weather data at the township level was provided by Alberta Agriculture Forestry and Rural Economic Development (AAFRED) and Alberta Climate Information Service (ACIS) (2022). Field-level observations for precipitation and evapotranspiration were generated by randomly sampling values from a truncated normal distribution using the 30-year growing season mean, standard deviation, and maximum and minimum values. Figure 3 highlights the distribution of mean growing season precipitation and potential evapotranspiration within the province.

The fraction of low-lying terrain within each field level observation was randomly generated following a uniform distribution with a lower and upper limit equal to 0.0 and 0.10, respectively. The range of values was selected to account for likely producer decisions and to reflect the cost of inputs and availability of technologies, like variable rate application and sectional control (Vinco et al., 2022). This research assumes

[2] Eco-districts are subdivision of Eco Regions and part of the National Ecological Framework of Canada. They comprise of areas with similar biological and climatic characteristics. Eco-district sizes vary but a minimum size requirement is set at 100,000 ha (1,000 km2) (Agriculture and Agri-Food Canada, 2013). The grid system used in this analysis is part of the Alberta township survey system which divides the province into equal-sized parcels of land that are 6 by 6 miles, 9.7 by 9.7 km (~9,400 ha) (Government of Alberta, 2022).

that producers would avoid applying fertilizer on large areas of the field that would be saturated throughout the growing season due to the decreased return on investment.

For this analysis, soils in Alberta were assumed to be medium textured with an $RF_{TX,i}$ value equal to one. This assumption follows previous versions of the NIR, which did not apply a soil texture factor to Prairie soils, given the lack of correlation between texture and emissions in low precipitation areas (Environment and Climate Change Canada, 2021). While this assumption was updated in the 2022 NIR, minimal differences in emissions can still be observed in areas with low growing season precipitation levels (Environment and Climate Change Canada, 2022b). The relationship between precipitation and emissions is highlighted in Figure 4.

Ratio Factors

The Can2 model differentiated the base emission factor by nitrogen source in the 2022 National Inventory Report (Environment and Climate Change Canada, 2022b). The model differentiated between two sources, organic and inorganic fertilizer, with $RF_{NS} = 1$ for inorganic and $RF_{NS} = 0.84$ for organic sources. The model, however, does not account for the use of enhanced-efficiency nitrogen fertilizers[3]. To account for the effects of enhanced efficiency products, this analysis added additional RF_{NS} values for polymer-coated urea (PCU), nitrification inhibitors (NI), urease inhibitors (UI), and double inhibitors (DI) with the values based on a synthesis of meta-analytical studies by Bourassa, Fournier, and Vinco (2022). The ratio factors N_2O mitigation and yield $\left(RF_{Yield,s}\right)$ were generated following a uniform distribution. The upper and lower bounds of the uniform distribution were based on the confidence intervals for average effect by EENF type, see Figure 5.

Cost-Benefit Analysis

The cost-benefit analysis was evaluated based on the change in net revenue on a per hectare basis resulting from adopting EENF products compared with conventional fertilizers. Equation 6 shows how the change in net revenue was calculated for each of the four enhanced efficiency products included in the analysis.

[3] This omission is not uncommon, compared to other country-specific methodologies in 2021, only 2 countries differentiate emission factors for inhibitors, Japan and Ireland (Duffy et al., 2021; Ministry of the Environment & National Institute for Environmental Studies, 2021), and zero for coated products (Bourassa & Vinco, 2022).

$$
\begin{aligned}
\Delta REV_{f,t,z,s=CRN,c} &= \left(\Delta Y_{f,z,s=CRN} * Pr_f\right) + \left(.66 \times \left[\frac{\Delta N_2O_{f,t,z,s=CRN} \times 298}{1000}\right] \times CP_c\right) - \left(C_{f,s=CRN} \times N_{Fert,f,z}\right) \\
\Delta REV_{f,t,z,s=DI,c} &= \left(\Delta Y_{f,z,s=DI} * Pr_f\right) + \left(.66 \times \left[\frac{\Delta N_2O_{f,t,z,s=DI} \times 298}{1000}\right] \times CP_c\right) - \left(C_{f,s=DI} \times N_{Fert,f,z}\right) \\
\Delta REV_{f,t,z,s=NI,c} &= \left(\Delta Y_{f,z,s=NI} * Pr_f\right) + \left(.66 \times \left[\frac{\Delta N_2O_{f,t,z,s=NI} \times 298}{1000}\right] \times CP_c\right) - \left(C_{f,s=NI} \times N_{Fert,f,z}\right) \\
\Delta REV_{f,t,z,s=UI,c} &= \left(\Delta Y_{f,z,s=UI} * Pr_f\right) + \left(.66 \times \left[\frac{\Delta N_2O_{f,t,z,s=UI} \times 298}{1000}\right] \times CP_c\right) - \left(C_{f,s=UI} \times N_{Fert,f,z}\right)
\end{aligned} \tag{6}
$$

The additional net revenue from the adoption of PCU, DI, NI, or UI at carbon price c, was calculated by adding the change in production revenue to the carbon offset revenue and subtracting the cost of adoption. Production revenue was calculated by multiplying the difference in yield $\left(\Delta Y_{f,z,p,s}\right)$[4] by the price of wheat $\left(Pr_f\right)$[5]. Offset revenue was calculated by multiplying the change in emissions, measured in tonnes of CO_2 equivalent by the price of carbon CP_c. Three separate prices were evaluated for this analysis.

1. \$0 a tonne CO_2eq (no offset provided)
2. \$50 a tonne CO_2eq (current carbon price as of 2022)
3. \$170 a tonne CO_2eq (expected carbon price for 2030)

The total offset value was multiplied by 0.66 to account for the producer-aggregator split. Lastly, the cost of adoption was calculated by multiplying the per kilogram premium for enhanced efficiency products $\left(C_{f,s}\right)$ by the nitrogen application rate. The price premium for inhibitor products was provided by Koch Agronomic Services. Representative Price premiums for UIs, NIs, and DIs were based on prices for Agrotain and ANVOL, Centuro, and SuperU, respectively. The price premium for CRF was based on ESN, produced by Nutrien[6]. The range of prices for each product can be found in, Table 2, with values generated for each field level observation following a uniform distribution using the ranges provided.

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[4] For each field in each risk zone a yield value $\left(Y_{prod,f}\right)$ was randomly sampled from normal distribution using the risk zone mean and standard deviation with the values limited to between the 7-year maximum and minimum values. The additional yield from EENF adoption was then calculated by multiplying the yield by the EENF yield ratio factor assigned to the field.
[5] Wheat prices ranged between \$6.79 and \$7.28 and were based on the maximum and minimum average monthly wheat prices between 2017 and 2021 (Statistics Canada, 2022). Values were randomly assigned to each field following a uniform distribution.
[6] It is important to note that ESN is generally blended with other nitrogen fertilizers at a rate between 50 and 100 percent ESN. For this analysis, it is assumed that 100 percent of fertilizer applied is ESN, this assumption is in line with the review literature which generally compares CRF to conventional fertilizer and does not include mix.

Table 1

Summary of Model Input Variables

Variable	Units	Distribution	Source
$P_{f,t}$	mm	Normal (truncated)	(AARFED & ACIS, 2022)
$PE_{f,t}$	mm	Normal (truncated)	(AARFED & ACIS, 2022)
$Yield_{f,z}$	bu/ac	Uniform	(AFSC & AF, 2015:2021)
$Y_{prod,f}$	bu/ac	Normal (truncated)	(AFSC & AF, 2015:2021)
$FR_{Topo,f}$	Unitless	Uniform	
$RF_{TX,f}$	Unitless	Constant	(ECCC, 2021)
$RF_{f,NS,CRF}$	Unitless	Uniform	
$RF_{f,NS,NI}$	Unitless	Uniform	
$RF_{f,NS,UI}$	Unitless	Uniform	
$RF_{f,NS,DI}$	Unitless	Uniform	(Bourassa et al., 2022)
$RF_{f,Yield,CRF}$	Unitless	Uniform	
$RF_{f,Yield,NI}$	Unitless	Uniform	
$RF_{f,Yield,UI}$	Unitless	Uniform	
$RF_{f,Yield,DI}$	Unitless	Uniform	
$C_{f,s=CRF}$	\$/kg N	Uniform	(Nutrien, 2022)
$C_{f,s=NI}$	\$/kg N	Uniform	(Koch Agronomic Services, 2022)
$C_{f,s=UI}$	\$/kg N	Uniform	(Koch Agronomic Services, 2022)
$C_{f,s=DI}$	\$/kg N	Uniform	(Koch Agronomic Services, 2022)
Pr_f	\$/bu	Uniform	(Statistics Canada, 2022)

Table 2

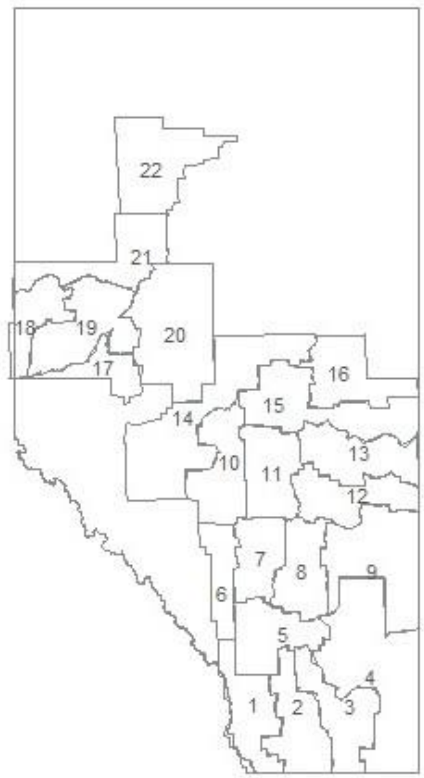
EENF Product Type and Prices

Product	Brand	Reported Price	Reported Units	Converted Price	Units
CRF	ESN	0.16 - 0.20	$/lb Urea	0.77 - 0.96	$/kg N
NI	Centruro	0.09 - 0.12	$ /lb N	0.20 - 0.26	$/kg N
UI	Agrotain/Anvol	0.08 - 0.10	$ /lb N	0.18 - 0.22	$/kg N
DI	SuperU	135 - 145	$/t Urea	0.29 - 0.32	$/kg N

Note: Pricing information for nitrogen stabilizers was provided through personal communications with Koch Agronomic Services and based on 2021 prices (Koch Agronomic Services, 2022). Pricing for ESN was based on the premiums used in Nutrien's ROI calculator (Nutrien, 2022).

Figure 1

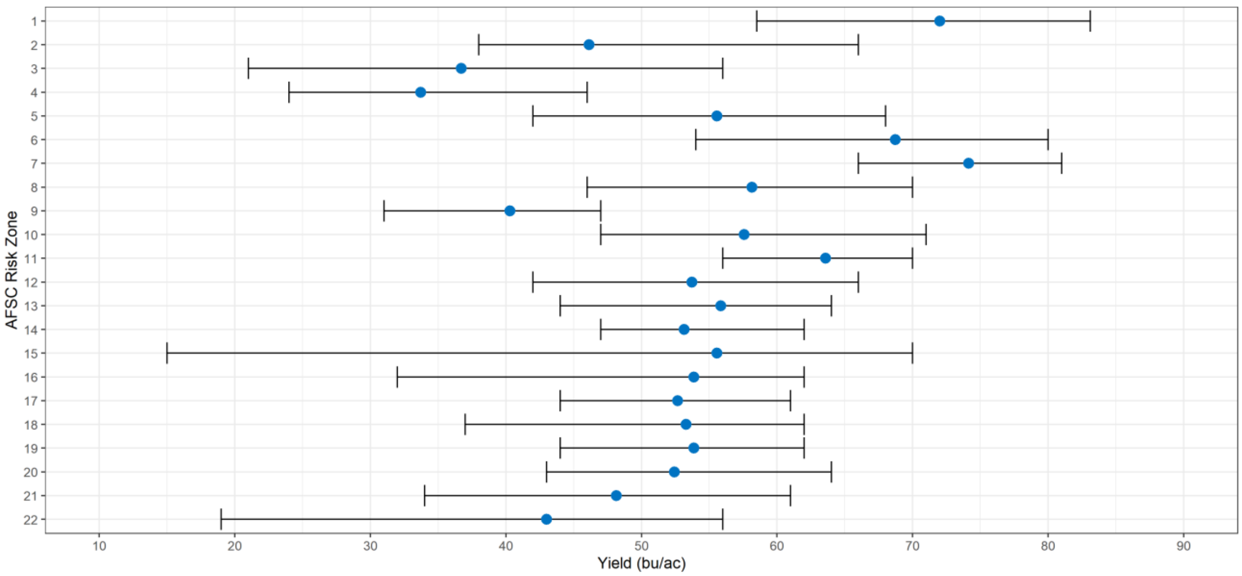
Alberta Agricultural Risk Zones Map



Note: Risk Zone boundaries are approximate and based on a trace of the AFSC Risk Zone Map published in the 2021 edition of Yield (AFSC & AF, 2021)

Figure 2

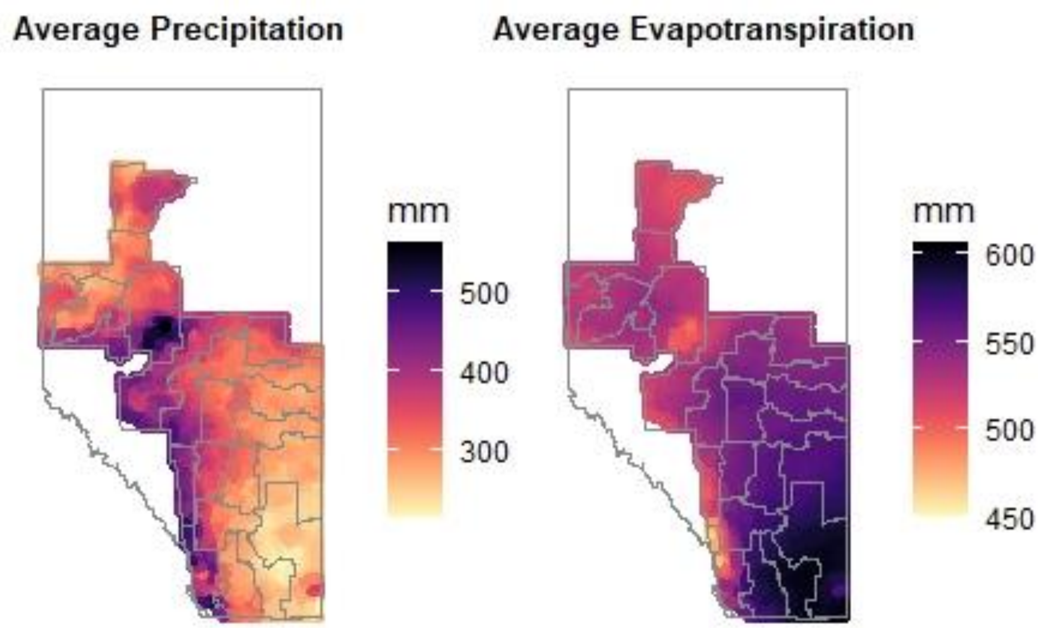
Average, Minimum, and Maximum Yield by AFSC Risk Zone



Note: The 7-year yield average for the specified Risk Zone is indicated by the blue point. The range plot indicates the maximum and minimum average annual wheat yield. Data for figure was manually collected from publicly available editions of Yield Alberta covering a 7-year period from 2014 to 2020 (AFSC & AF, 2015, 2016, 2017, 2018, 2019, 2020, 2021).

Figure 3

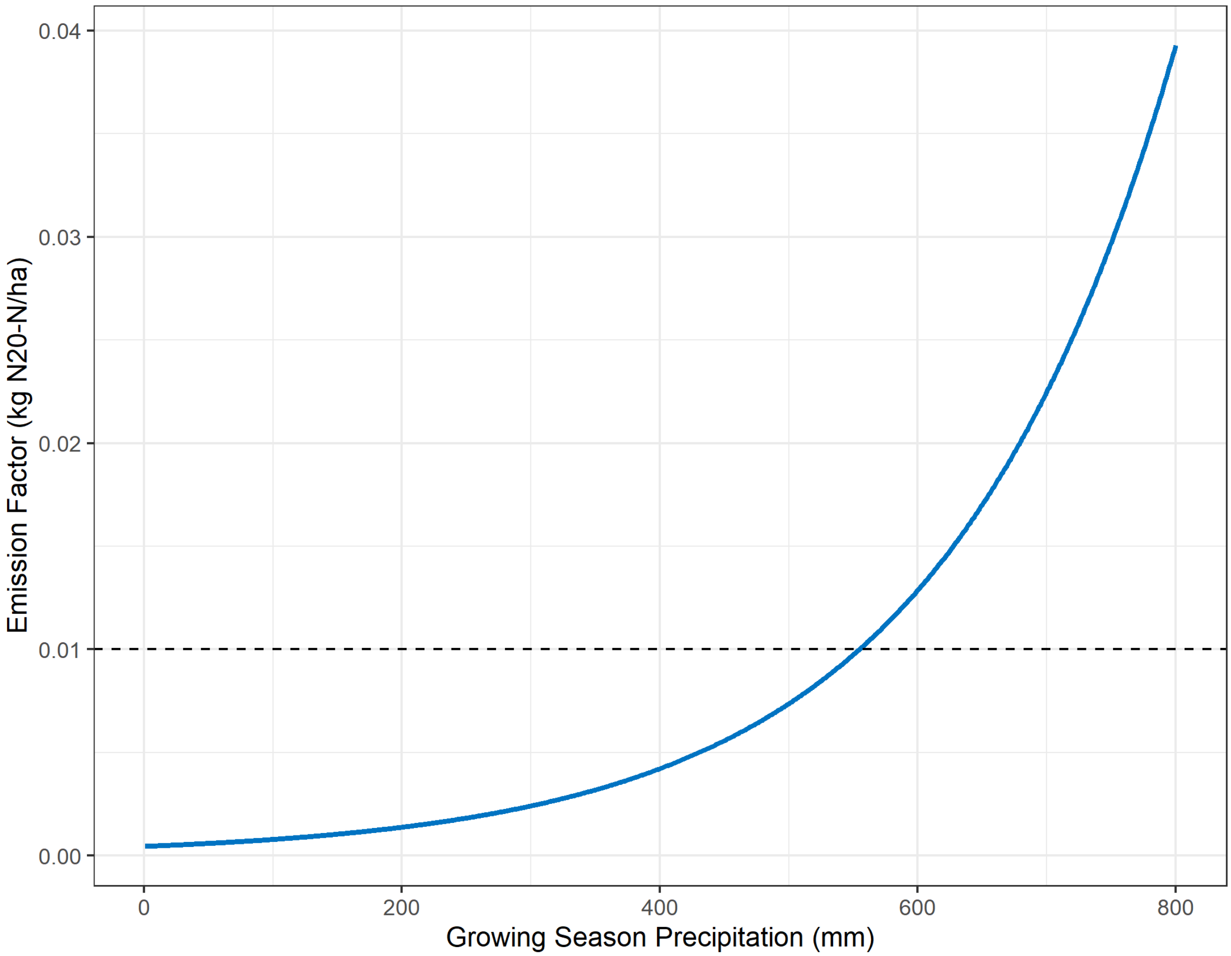
Average Growing Season Precipitation and Evapotranspiration by Township and Risk Zone



Note: 30-Years Average growing season precipitation and evapotranspiration was based on daily interpolated data for each of the 3555 townships included within the analysis. Data was provided by Alberta Agriculture, Forestry and Rural Economic Development, Alberta Climate Information Service (ACIS) https://acis.alberta.ca (2022).

Figure 4

Relationship Between Precipitation and Emissions Factor

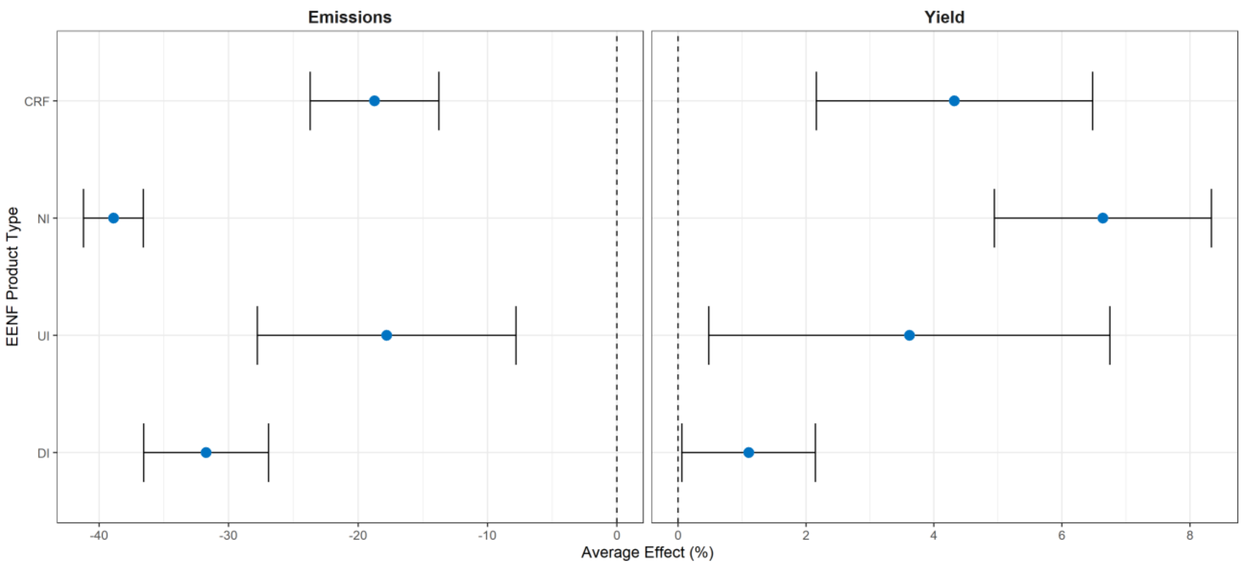


Note:

Emission factor was estimated using Equation 4. The horizontal dashed line indicates the IPCC default emission factor value.

Figure 5

Effects of EENF Adoption on Direct Fertilizer-Based N_2O Emissions and Yield



Note: The Range plot indicates the 95 percent confidence interval for the average effect (blue point) of EENF adoption on both yield and emissions. The figure is based on results from a synthesis of meta-analytical studies by Bourassa et al. (2022).

Results and Discussion

Emission Factor

At the provincial level, the mean dryland emission factor was found to be 0.0036 kg N_2O-N kg N^{-1} and a median value of 0.0030 kg N_2O-N. The interquartile range (IQR) of results was between 0.0023 and 0.0042. At the risk zone level, median values ranged from 0.0024 kg N_2O-N kg N^{-1} in Risk Zone 4 to 0.0050 kg in Risk Zone 6, located in the South Region of the province, and can be viewed in Figure 6. Within the Central and North Regions, emission factors at the median were estimated to fall within the range of 0.0027 kg to 0.0043 kg and 0.0029 kg to 0.0044 kg N_2O-N kg N^{-1}, respectively. Figure 6 shows the cumulative distribution function for the estimated emission factors at both the provincial (black dashed line) and risk zone levels. The y-axis indicates the percentile, which can be interpreted as the probability of being at or below a specific emission factor value.

The 2021 NIR disaggregated emission factor estimates published for the Prairie region were 0.002 and 0.008 kg N_2O-N kg N^{-1} for brown and black/grey soil regions, respectively (Environment and Climate Change Canada, 2021). Results for this analysis fall within this range, slightly overestimating emission factors for brown soil regions and underestimating black soil regions. The change in methodology in 2022 which introduced an exponential relationship between precipitation and emission factor, replacing a linear relationship, partially explains the difference between results (Environment and Climate Change Canada, 2021, 2022b). When compared to other emission factor estimates, the analysis results were above the IPCC emission factors for dry climate non-irrigated production of 0.001 kg N_2O-N kg N^{-1}, and below the dry temperate region factor of 0.007 kg (IPCC, 2019). Compared with Australia, which uses a country-specific Tier 2 approach that differentiates by production type, the emission factor used for non-irrigated crop production, 0.002 kg N2O-N kg (Australian Government Department of Industry Science Energy and Resources, 2021), was similar to median emission factors found in southeast Alberta (Risk Zones 3, 4, and 9).

Emissions

The compounding effect of the emission factor and nitrogen application rate can be observed in the variation in N_2O emission estimates in Figure 7. he differences in the estimated emission levels are much larger than suggested by the emission factor and application rates alone. The province's emissions per hectare fell within the range of 0.022 and 27.084 kg N_2O ha^{-1}. The mean and median values were estimated to be 0.615 and 0.46 kg N_2O, respectively. As a result of the simulation, several extreme values were generated. A more plausible range can be observed when examining the middle 98 percent, 0.077 kg to 2.35 kg N_2O ha^{-1}, or the IQR, 0.26 kg to 0.68 kg.

The spatial distribution of N_2O at the township level can be observed in Figure 8, which provides the estimated median emissions within each township. Figures 7 and 8 show that South Region Risk Zones have the largest distribution of results. Within Risk Zones 3, 4, and 9, median emissions were 0.22 kg N_2O ha^{-1}, 0.15 kg, and 0.20 kg respectively, and at the 99th percentile were just 0.61 kg, 0.41 kg, and 0.40 kg. In contrast, Risk Zones 1, 6, and 7, located in the southwest of the province, which had higher average rainfall and yield potential, had median emissions of 1.10 kg N_2O ha^{-1}, 1.16 kg, and 0.87 kg, and had 32, 29, and 5.7 percent of observations above 1.5 kg N_2O ha^{-1}.

Mitigation Potential and Offset Values

Median mitigation potential for EENF adoption at the provincial level was estimated to be 0.084 kg N_2O per hectare (IQR: 0.052 - 0.129), 0.178 kg (IQR: 0.111 - 0.266), 0.076 kg (IQR: 0. 044 - 0.125), and 0.144 kg (IQR: 0.090 - 0.218) for CRF, NI, UI, and DI, respectively. On a per hectare basis, the emissions reductions would equate to total offset values[7] (TOV) of $1.26 (IQR: $0.77 - $1.92), $2.65 (IQR: $1.65 - $3.97), $1.14 (IQR: $0.67 $1.85), and $2.15 (IQR: $1.34 - $3.24) at $50 a tonne of CO_2eq, and $4.27 (IRQ: $2.63 - $6.52), $9.00 (IRQ: $5.63 - $13.49), $3.86 (IRQ: $2.24 - $6.29), and 7.32 (IRQ: $4.55 - $11.02) at $170 per tonne, see Figure 7.

As the ratio factor does not vary based on environmental conditions, higher-emission regions have a higher mitigation potential and carbon offset value than lower-emission regions. This difference is seen in the South

[7] TOV is calculated my multiplying total emission reduction, measured in CO_2eq, by the carbon price. It does not account for the aggregator split which is generally between one and two thirds the TOV.

Region of Alberta where the largest emission variation is observed. Figures 9 and 10 provides the distribution of risk zone level results within the South Region of Alberta for each EENF type, for the estimated offset value at \$50 t CO_2^{-1}. Median offset values for CRF had a per hectare estimated range between \$0.40 in Risk Zone 4 (IQR: \$0.29 - \$0.55) to \$3.20 (IQR: \$2.31- \$4.51) in Risk Zone 6. For NIs UIs, and DIs values had a range between \$0.84 (IQR: \$0.61 - \$1.14) to \$6.70 (IQR: \$4.92 - \$9.30), 0.36 (IQR: \$0.24 - \$0.54) to 2.96 (IQR: \$1.99 - \$4.40), and 0.68 (IQR: \$0.49 - \$0.93) to 5.45 (IQR: \$3.99 - \$7.61) per hectare, respectively.

Additional Net Revenue from Adoption

Figure 11 provides the cumulative distribution of the estimated additional net revenue from EENF adoption at the provincial level. Both NI and UI products were effective at increasing net revenue for the overwhelming majority of observations. In both cases this was accomplished without the introduction of carbon offsets (carbon price equal to \$0), suggesting that low adoption rate maybe a result of barriers to adoption other than financial factors. DI and CRF products were found on average to have a negative effect on additional net revenue when no offsets were provided. At \$170 a tonne, the majority of observations at the provincial level were still negative for DI and CRF products.

At the provincial level, the median change in net revenue for CRF products was -\$11.75 per hectare with the IQR between -\$24.33 and -\$0.21. The revenue neutral point was observed in the 76th percentile indicating that only the top 24 percent of field level results were associated with positive additional net revenue results. Unsurprisingly, once carbon offsets were provided, both additional net revenue and the percentage of positive observations increased; however, the magnitude of the changes were not substantial. At \$50 per tonne, additional net revenue increased to -\$10.74 (IQR: -\$23.15 - \$0.63) and the percentage of positive observations increased to 26 percent. At \$170 a tonne the median increased to -\$8.31 per hectare (IQR: -\$20.37 - \$2.74) and positive results were found in 31 percent of observations.

At the Risk Zone level, a relationship between the nitrogen application rate and changes in net revenue can be observed. Median results were found to be more negative in risk zones with high nitrogen requirements. For example, at the 50th percentile in Risk Zone 1 the change in Net Revenue was estimated to be -\$32.57 per hectare (IQR: -\$45.95 – (-\$18.82)), while in Risk Zone 4, which has lower nitrogen requirements due to low yield potential, the median value was \$3.81 per hectare (IQR: -\$3.43 - \$11.46). This pattern is a result of the high per unit premium for CRF products between $0.77 - $0.96 per kilogram of nitrogen, which more than offset the additional revenue resulting from higher yields. Conversely, higher nitrogen requirement risk zones benefited the most from the development of carbon offsets programs, given larger mitigation potentials. For example, when comparing Risk Zone 1 to Risk Zone 4, at $170 a tonne the median change in net revenue increased by $9.01 ha compared to $0.98 in Risk Zone 4, see Figure 12.

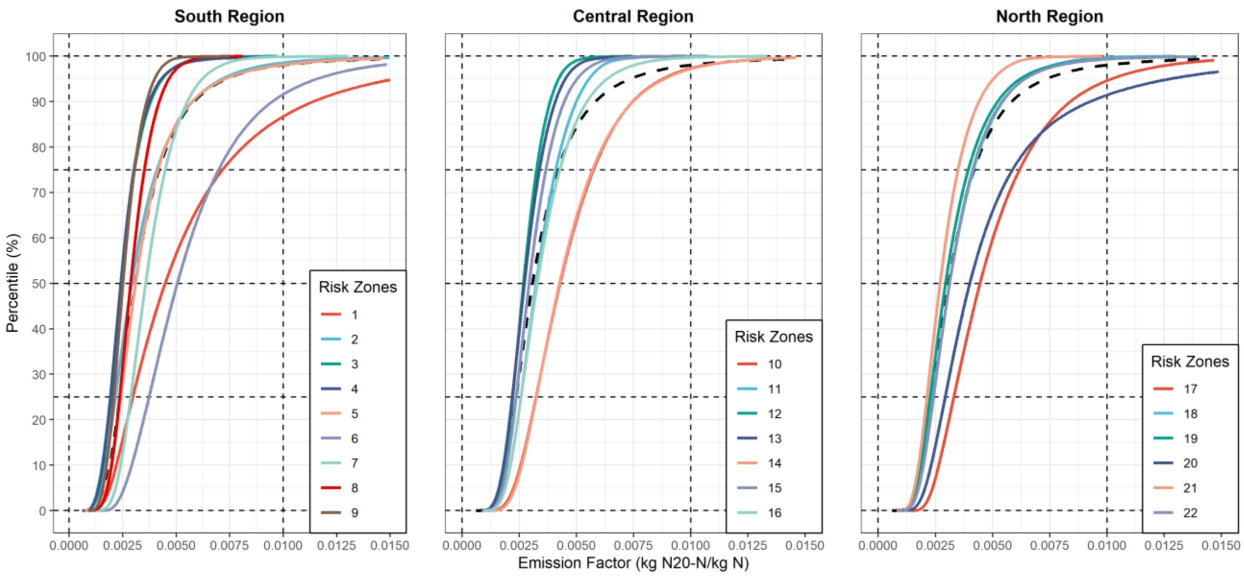
NI products were the most effective at both decreasing emissions and increasing yields. Combined with a low per unit cost of adoption, it is unsurprising that at the provincial level, over 99 percent of the total NI observations resulted in a positive change in net revenue, even when no offset was provided, see Figure 13. At the median, the change in net revenue was observed to be $44.31 (IQR: $35.35 - $54.54) at a carbon price of $0, which increased to $46.41 (IQR: $37.08 - $57.01), and then to $51.22 (IQR: $40.78 - $63.00) once offsets were provided. Examining the risk zone level results in Figure 11, the change in net revenue appeared to correlate with risk zone yield potential, as high yield zones had high median change in net revenue. High yielding zones also had the highest mitigation potential and benefited the most from offset programs. At a premium of between $0.20 - $0.26 a kg of nitrogen, the increased revenue from higher yields exceeded offsetting the cost of adoption, even with high nitrogen requirements.

UIs were effective at increasing net revenue in the majority of observations. When no offsets were provided, 87 percent of observations were observed to have positive net revenues; this value increased to 88 percent at a $50 a tonne offset and to 92 percent at $170 a tonne, see Figure 14. Median net revenue increased from $19.12 a hectare (IQR: $6.02 - $33.13) to $20.01 (IQR: $6.91 - $34.09) and then to $22.13 (IQR: $9.00 - $36.43) at $170 a tonne. Similar to NIs, a relationship between yield potential and change in net revenue was observed. At the 50th percentile, high-yield regions had more positive changes in net revenue than in lower-yielding regions. However, when compared to NIs, the adoption of UI products led to lower overall changes in net revenue, due to decreased mitigation potential and lower average effect on yield.

Double Inhibitors provide an interesting case study when compared to other EENF products. As seen in Figure 15, DIs were found to be highly effective at reducing emissions, but only marginally effective at increasing yield. As a result, most observations were found to have a negative net return, with only 13 percent above the revenue neutral point when no offset was provided. However, given the narrow range of results and proximity of results to the revenue-neutral point, DIs maybe the only EENF at the provincial level to significantly benefit from the development of offset protocols. At $50 a tonne, the percentage of observations with positive net revenue from adoption increases to 19 percent, and then to 38 percent at $170. At the 50th percentile, values were found to be -$7.67 (IQR: -$13.33 - -$2.79) and -2.31 (IQR: -$7.14 - $2.48) at $0 and $170 a tonne respectively. As seen in Figure 14, the potential benefits of carbon offsets programs can be clearly observed. High emission risk zones, such as 1, 6, and 7, have limited incentives to adopt DI products given the cost of adoption and limited yield benefit. However, given the large mitigation potential of DI products, large offsets can be generated, potentially largely offsetting cost of adoption. When no offset was provided, median results were -$6.64 in Risk Zone 1 with a revenue neutral point above the 99th percentile; at a $170 a tonne, offset median change in net revenue increased to -$3.06 and the percent of positive results increased from less than 1 percent to 40 percent.

Figure 6

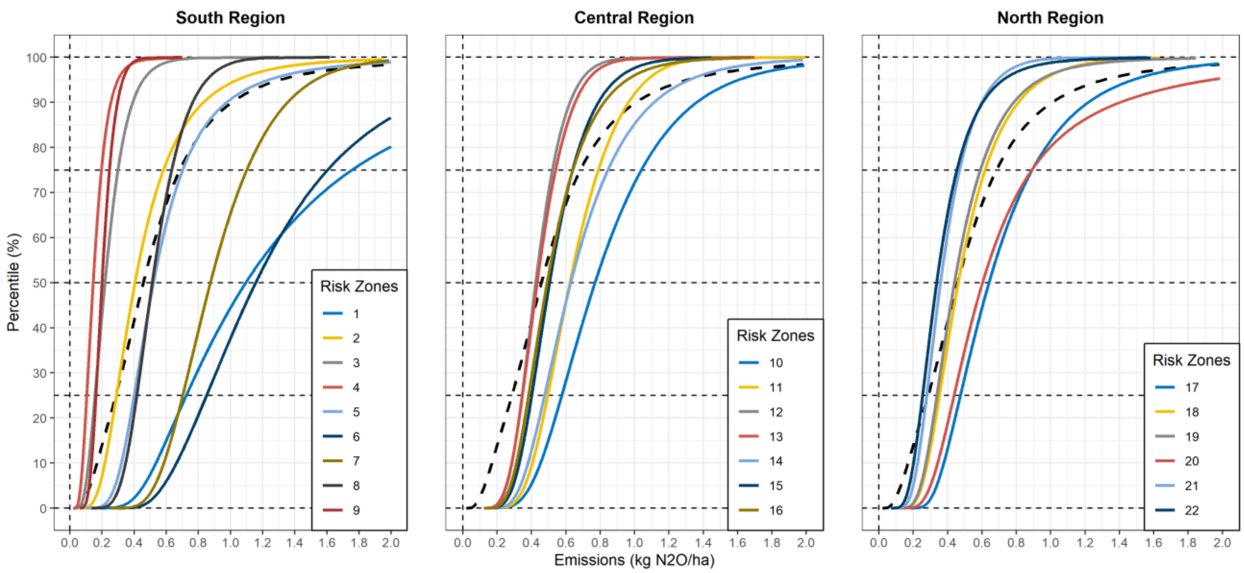
Cumulative Distribution of Emission Factors by AFSC Risk Zones



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The black dashed distribution indicates provincial level results. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles. The vertical dashed lines indicate 0 and the IPCC default value (0.01 kg N_2O-N kg N^{-1}).

Figure 7

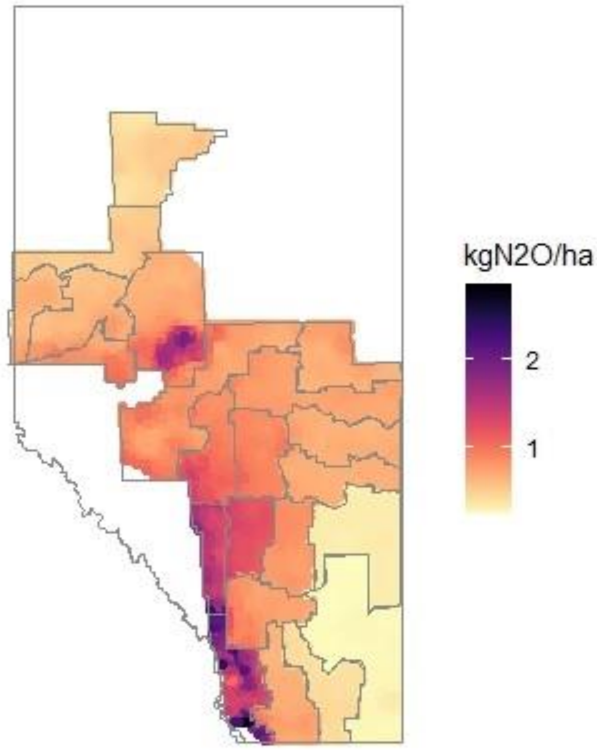
Cumulative Distribution of Direct Fertilizer Based N_2O Emissions by AFSC Risk Zones



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The black dashed distribution indicates provincial level results. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Figure 8

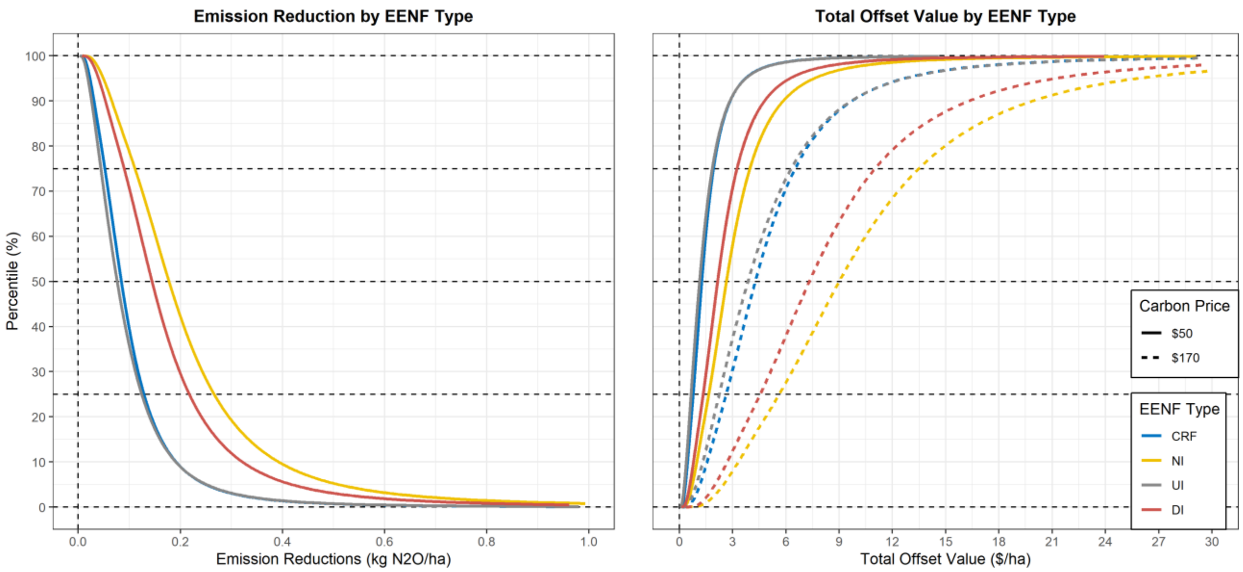
Median Direct Fertilizer Based N_2O Emissions by township



Note: Median township level emission estimate measured in kg N_2O per hectare. Boundaries on map indicate approximate boundaries of AFSC Risk Zones.

Figure 9

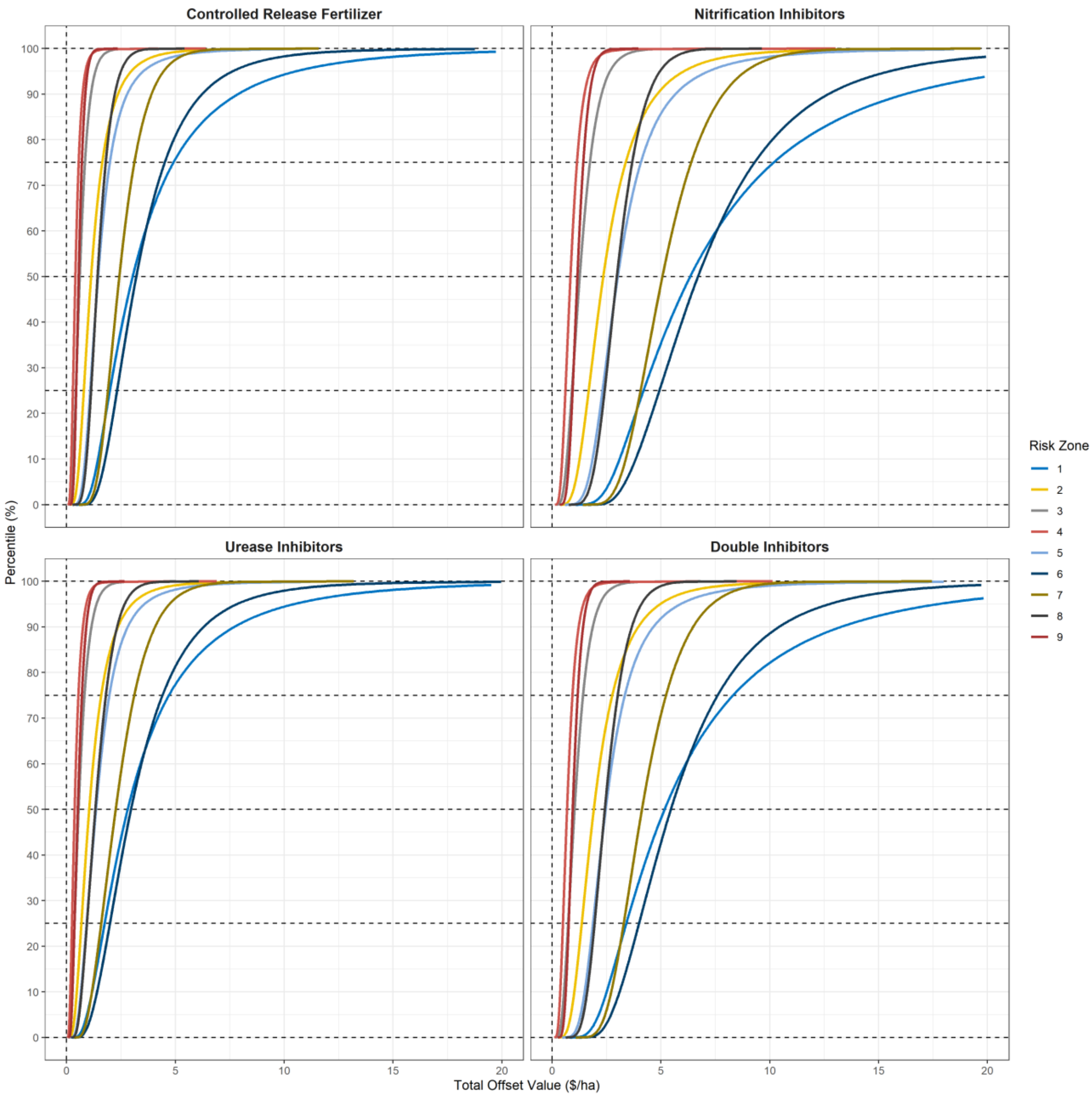
Cumulative Distribution of the Change in Emissions and Total Offset Value by EENF Adoption



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The black dashed distribution indicates provincial level results. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Figure 10

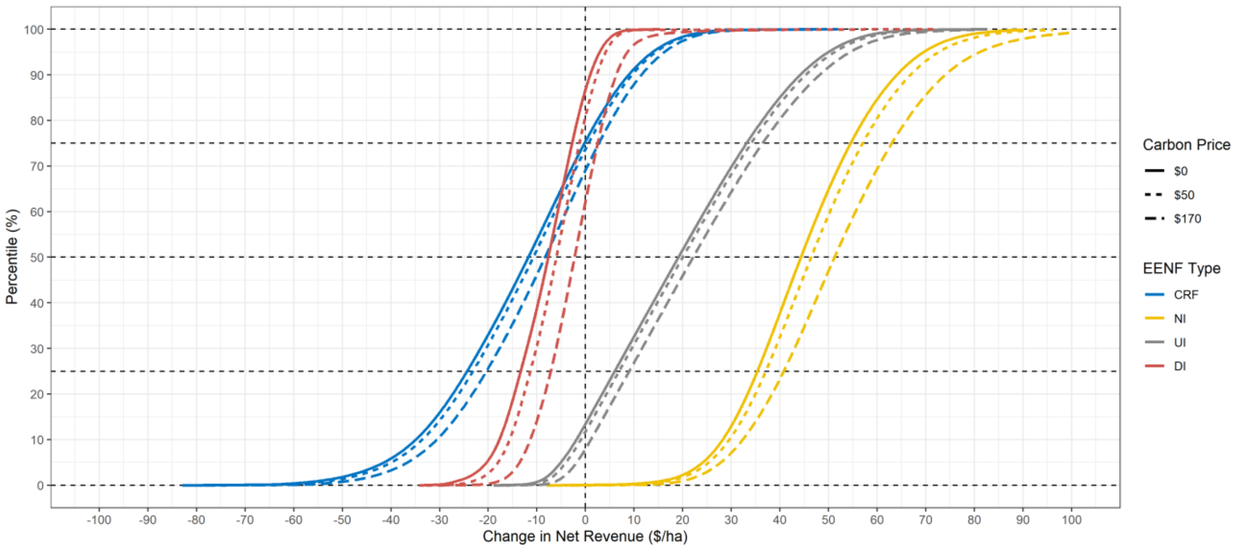
Cumulative Distribution of Total Offset Value by Risk Zones



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Figure 11

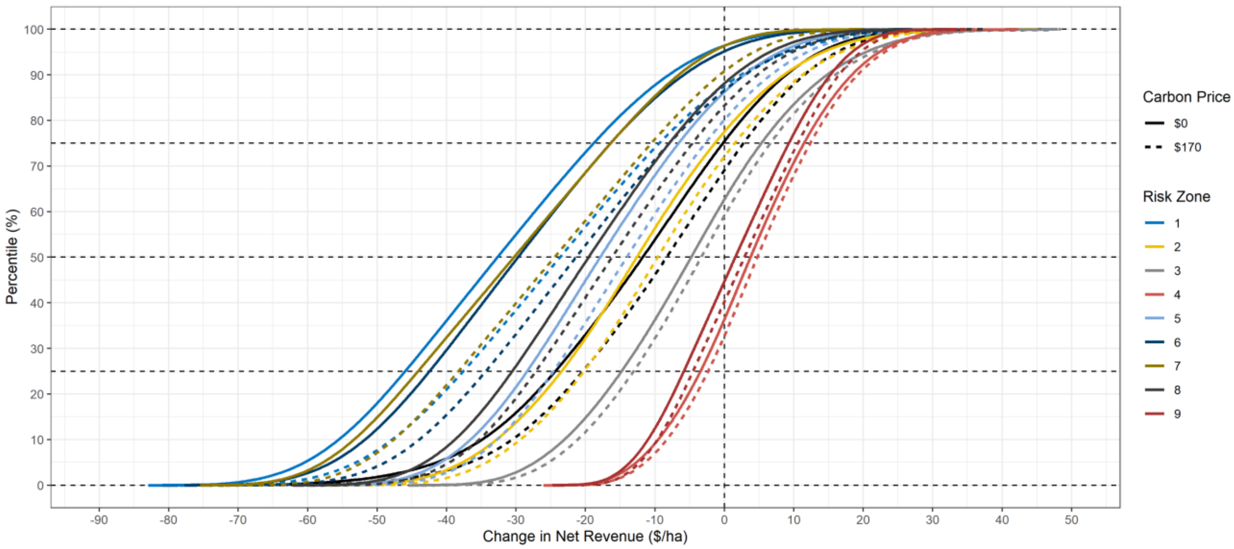
Cumulative Distribution of Additional Net Revenue from EENF Adoption



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Figure 12

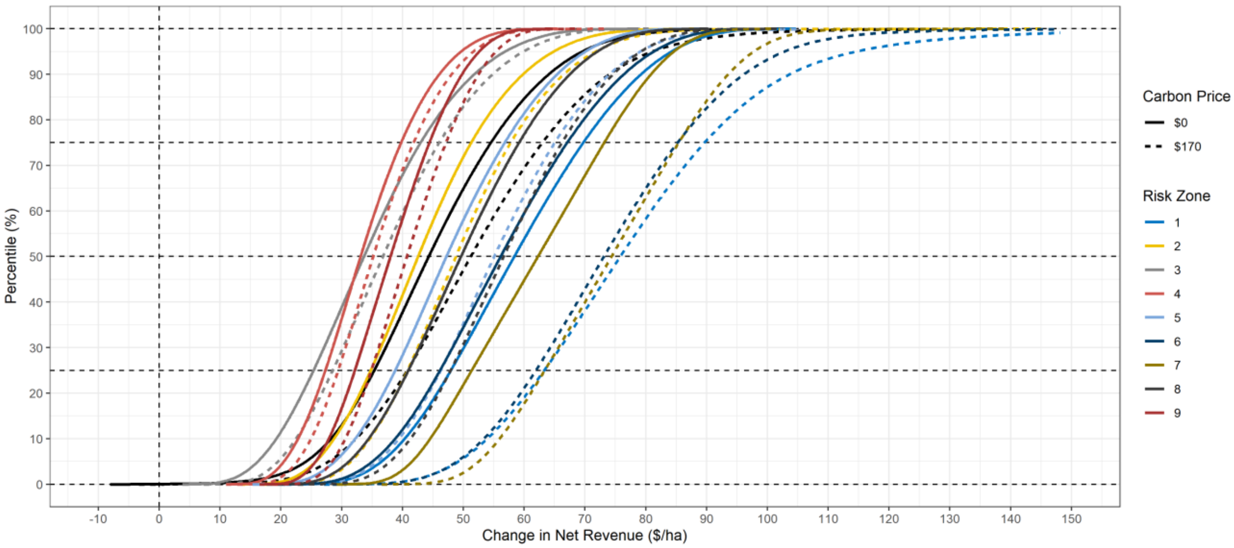
Cumulative Distribution of Additional Net Revenue from CRF Adoption by Township



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Figure 13

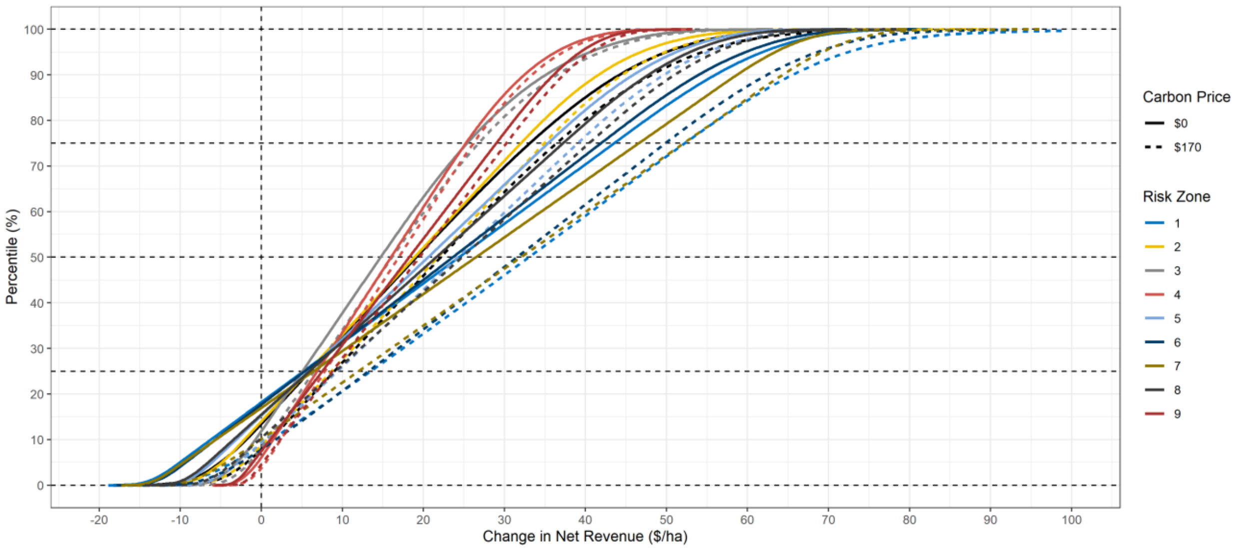
Cumulative Distribution of Additional Net Revenue from NI Adoption by Township



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Figure 14

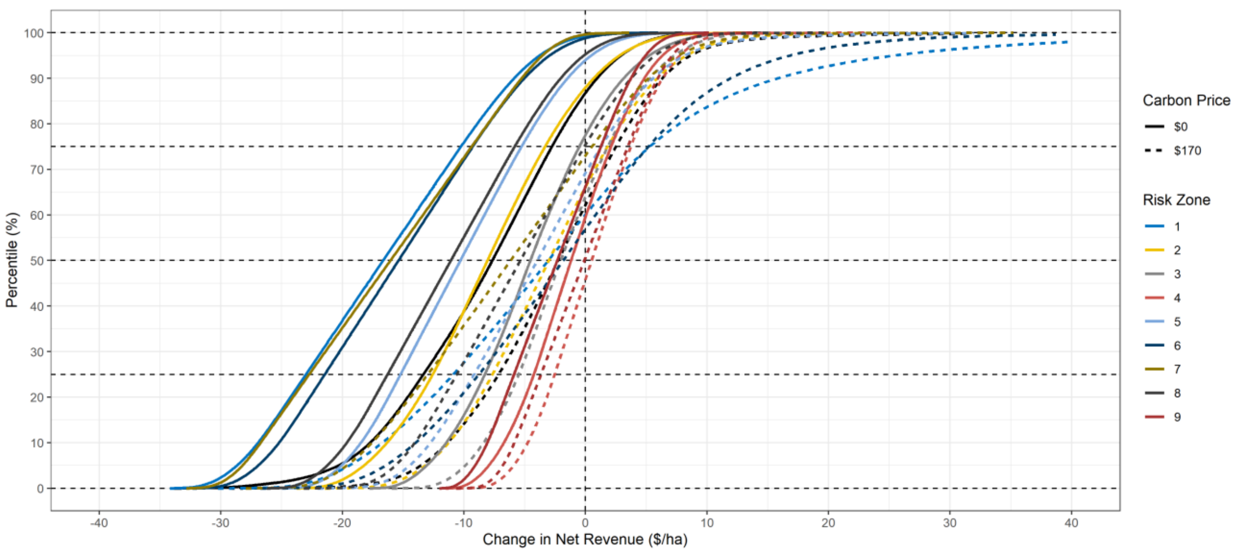
Cumulative Distribution of Additional Net Revenue from UI Adoption by Township



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Figure 15

Cumulative Distribution of Additional Net Revenue from DI Adoption by Township



Note: The cumulative distribution indicates the probability of being at or below a specific emission factor value. The horizontal dashed lines indicated the maximum and minimum, and the 25th, 50th, and 75th percentiles.

Conclusion

Canada has set an ambitious target to reduce fertilizer-based greenhouse emissions by 30 percent of 2020 levels by 2030. This will require a reduction of at least 3.77 Mt of CO_2eq over the next eight growing seasons (Agriculture and Agri-Food Canada, 2022). The 2022 AAFC discussion document does provide some indication of where the federal government believes emissions can be reduced but does not provide a clear plan as to how adoption of BMPs are going to be encouraged or incentivized. The document clearly shows that to meet the emission reduction target, near universal adoption of EENFs, particularly in the Canadian prairies, will be required. If BMP adoption will be strictly voluntary, significant consideration as to the effects BMP adoption on the farmer's bottom line will be required.

This research demonstrated that EENF adoption can increase net revenue for producers even when no incentivization is provided. However, the results are highly dependent on EENF product type, risk zone, and assumptions made about mitigation and yield potential. Given these findings, it begs the question - why has more widespread adoption not occurred? Vinco et al. (2022) provides some insight as to why this may be the case. Within their paper, multiple interviewees mentioned that the "sticker shock" of EENF products may dissuade many producers from adoption, despite the potential return on investment. Another explanation is that the benefits of adoption may not be overly clear, particularly within the Palliser triangle region of the province, as mentioned in Ferguson et al (2019) "*If weather and soil conditions are not conducive to N loss, there is no benefit to protection against loss with the use of inhibitors.*" As demonstrated in our research, apart from Risk Zones 1, 6, 7, and 20, average growing season precipitation across the agricultural producing regions of the province is low, contributing to low per hectare emissions. This suggests that the benefits to producers may be limited in semi-arid regions of the province, as the risk of nitrogen loss is low. In both cases, increasing funding of provincial agricultural research and extension services in relation to EENF adoption would be highly beneficial. Increased research and extension would allow producers to have a better understanding of the expected return on investment and to identify where and under what production systems EENFs are appropriate. As highlighted in Vinco et al. (2022) both research and extension were identified as lacking by both producers and stakeholders in the interviews.

If the target is to be met by 2030 and if BMP adoption will be strictly voluntary, incentivization programs will have to be developed. Alberta has been a global pioneer in the development of carbon offsets for the agricultural sector, and in theory, NERP is well positioned to the challenge of the emission reduction target. However, the high administrative burden required for verification, the full suite of BMPs required for adoption, and the limited emission potential of dryland production, have made NERP a well-developed offset protocol with no participation (van Wyngaarden, 2022). Moreover, given the required role of aggregators, any financial benefit for producers is further discounted by one and two thirds (Alberta Agriculture Forestry and Rural Economic Development, 2018), significantly reducing incentive to participate within the program. Working within the existing system, simplifying NERP to focus exclusively on EENF adoption maybe effective at increasing adoption rates for producers at or above the revenue neutral level. Simplifying NERP would also reduce the administrative burden for producers, thereby decreasing the opportunity cost of participating within the program. However, the carbon offset program still faces several clear challenges, namely high upfront cost of adoption and low offset value linked to low per hectare emissions and aggregator fees. The development of a rebate program that leverages the existing infrastructure of TIER may be a more effective alternative to a simplified NERP. Under a rebate program, the value of the offset, minus administrative fees, would be applied automatically to the purchase of EENF products, reducing the upfront cost of adoption. The offset itself would be provided to the company selling the EENF product, functioning as its own aggregator and selling the offsets into TIER.

The pressure to reach the AAFC target of 30 percent reduction of N_2O emissions from fertilizer is mounting, with significant friction between government and industry throughout 2022. With only eight growing seasons left before 2030, the importance of reconciliation between government and industry is critical, supporting intersecting priorities and strength through unified efforts federally, provincially, and on-farm.

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