A Review of the Recent Scientific Literature Documenting the Impact of 4R Management on N_2O Emissions Relevant to a Canadian Context

Prepared for

Fertilizer Canada

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Table of Contents

List of Figures

List of Tables

Executive Summary

Nitrogen fertilizer management presents an opportunity to reduce the emissions of N_2O from agro-ecosystems in Canada. Fertilizer Canada has developed the 4R – Right Source, Right Place, Right Time, Right Rate – management system to improve the efficiency of fertilizer use in agriculture. The Nitrous Oxide Emissions Reduction Protocol (NERP) documents the implementation of 4R practices intended to reduce N_2O emissions. Here we review the science documenting the ability for 4R N fertilizer management practices to reduce N_2O emissions in Canadian agro-ecosystems.

Climate is one of the strongest influences on the potential for N_2O production in Canadian agro-ecosystems and is important in assessing the most important 4R practices to reduce these emissions. Climate has direct influence on soil water content which a major factor influencing the timing and nature of the microbial processes producing and consuming N_2O. Climate also has an indirect effect on the soils that form in the region and the cropping systems that are practiced. It is useful to differentiate the soils and cropping systems typical of the more arid prairie region of Canada form the more humid regions of the country in assessing the suitability of 4R practices for reducing N_2O emissions.

The 4R practice that most clearly result in reduced N_2O emissions are:
Source - The use of enhanced efficiency N fertilizer sources, in particular nitrification and urease inhibitors, has been shown to be a reliable means of reducing N_2O emissions.

Place - Fertilizer placement can increase the efficiency of fertilizer N use by reducing NH_3 emissions, but in some cases, this may result in increased N_2O emissions. It has also been shown that placement interacts with tillage system to influence N_2O emissions.

Timing – Reduction in N_2O emissions associated with fall application of N fertilizer, practiced in prairie Canada, can be achieved by delaying the application until soil temperature declines below 5 °C and/or by using urease/nitrification inhibitors. Split application of N fertilizers during the growing season is effective in reducing N_2O emissions when there is the potential for N_2O loss during the early growing season.

Rate – The greatest opportunities for reducing N_2O emissions are associated with lower rates of N fertilizer application. Better accounting for soil and residue N sources and targeting N rates for maximal N use efficiency have been shown to result in reduced N_2O emissions.

There are also opportunities for a reduction of N_2O emissions associated with non-4R practices. The consideration of crop rotation effects on carbon and nitrogen availability, impact of tillage system, the use of tile drainage and the inclusion of legumes in rotation are all important in assessing the potential for N_2O emissions and developing 4R practices to reduce N_2O emissions.

Introduction

One of the challenges in predicting the impact of fertilizer management on N_2O emissions is the nature of the processes that generate and/or consume N_2O and their dependence on soil moisture conditions. The primary processes producing N_2O are nitrification and denitrification and denitrification can also result in the consumption of N_2O. Which processes are active and what end-product is produced is influenced by soil water content. The water content of soils varies considerably between regions, seasons, within the landscape and from year-to-year. This makes the generalization as to the impact of a particular 4R management practice difficult. Often the impact will depend to a large degree on the context. Thus, the uncertainty expressed in the impact of a mitigation practice reflects both scientific uncertainty and the variability of N_2O emission potential associated with the conditions under which the practice was assessed. Correspondingly the outcomes of the implementation of a 4R suite will vary between locations and between years. The implementation of 4R management practices for N_2O emissions reduction is best viewed as an exercise in risk reduction and will often be situation/site specific. To assess the value of practices to reduce risk it is useful to understand the potential for N_2O production.

The Canadian Context

Nitrogen fertilizer use in Canada is the greatest of the crop nutrients and continues to grow more rapidly than the other major macronutrients (Fig. 1). Thus, the potential to produce N_2O and the N_2O emissions reported in Canada's GHG inventory are also increasing.

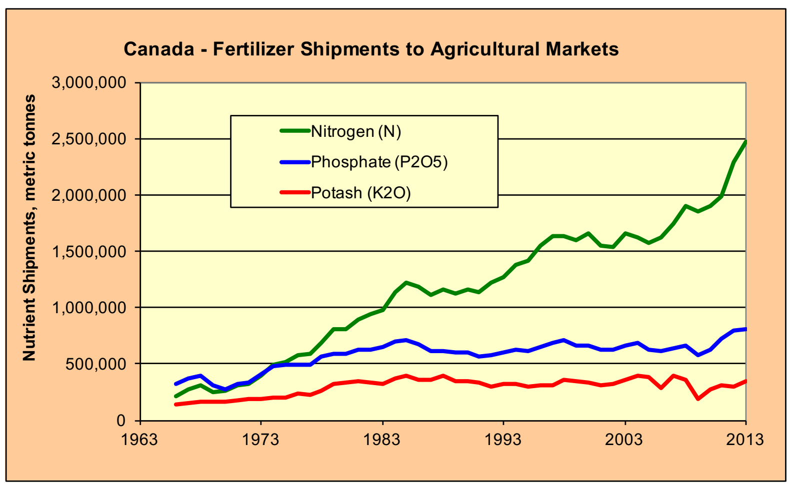

Figure 1: Sales of fertilizer macronutrients in Canada from 1966 to 2013 (IPNI based on Fertilizer Canada and Statistics Canada data)

Climate

As climate is a major determinant of the risk of N_2O emissions, delivering a national NERP program in Canada must recognize the diversity of its agro-ecozones and agricultural production systems and how they impact the sources of N_2O from agriculture and the most appropriate means of mitigating those sources. The risk of N_2O emissions also varies with season in the various regions in Canada. It is important that N_2O emissions reduction options are assessed in the context of climatic zone and season.

Climate and its impact on soil type, is one of the most fundamental attributes that defines Canadian agro-ecozones. In a recent meta-analysis, the single factor that explained the greatest amount of the variation in N_2O emissions was growing season precipitation, accounting for 38% of the variation in cumulative N_2O emissions (Rochette et al., 2018). At the site level, management was observed to have a greater impact on N_2O emissions than climate (Congreves et al., 2016). The majority of agriculture production in Canada occurs in four ecozones (Fig. 2):

Pacific Maritime - This ecozone has some of the warmest and wettest weather in Canada. Its maritime climate receives as little as 600 mm of precipitation per year in the lower Georgia Strait, while the area to the north is typically much wetter, receiving up to 3,000 mm. Compared to the rest of Canada, there is little variation in monthly temperatures. Averages in July range between 12 and 180C and, in January, between 4 and 60C. The frost-free period is up to 220 days long in the moist southerly valleys, decreasing to about 100 days in the mountains.

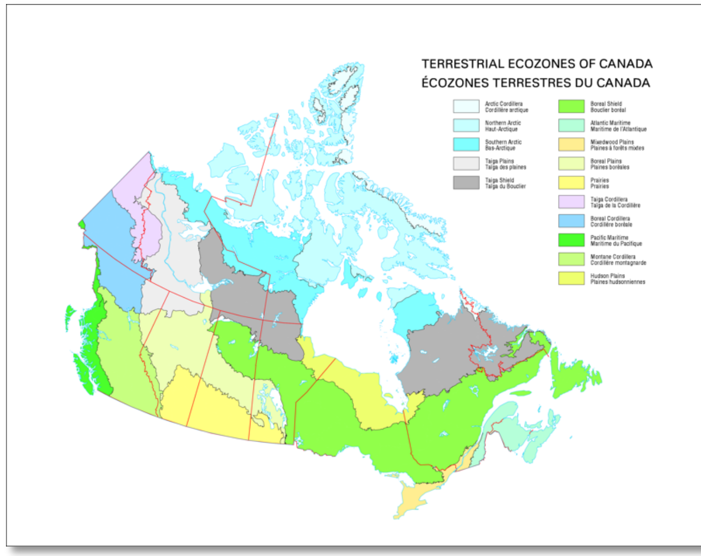

Figure 2: Terrestrial Ecozones of Canada (CanSIS)

Prairies extending into the Boreal Plains – This region is a pronounced, subhumid to semi-arid climate. Winters are very cold. Summers are short and warm. A water deficit is typical as the ecozone receives considerably less precipitation than other parts of Canada. Annual precipitation is extremely variable, ranging from 250 mm in the arid grassland regions of southwest Saskatchewan and southeast Alberta to slightly less than 700 mm in the Lake Manitoba plain, the warmest and most humid region in the Prairies Ecozone. About a quarter of the precipitation falls as snow.

Mixedwood Plains (Great Lakes/St. Lawrence Lowlands) - The climate of the Mixedwood Plains produces relatively warm summers and cool winters moderated by surrounding water bodies. Average annual growing season, north to south, ranging from 1,750 to 2,500 growing degree days above 5°C. This region also receives 720 to 1,000 mm of precipitation annually. Due to its location in the midst of a significant North American storm belt, weather in the Mixedwood Plains can change rapidly.

Atlantic Maritime - The proximity of the Atlantic Ocean creates a moderate, cool, and moist maritime climate. Most of the ecozone experiences long, mild winters (averaging about -4°C in January) and cool summers (the mean daily July temperature is 18°C). Average precipitation varies from 1,000 mm inland to 1,425 mm along the coast. The average annual growing season ranges from 1,500 to over 1,750 growing degree days above 5°C. Frost-free days, on average, fluctuate from 80 in the New Brunswick highlands to 180 along the coast. With a storm frequency, higher than anywhere else in Canada, sunshine can be a rare commodity.

The ratio of precipitation to potential evapotranspiration dictates the amount of water that remains in the soil and/or drains from the soil profile. (Rochette et al., 2008b) expressed the fraction of N inputs lost by leaching as a function of the ration of precipitation to potential evapotranspiration (Fig. 4).

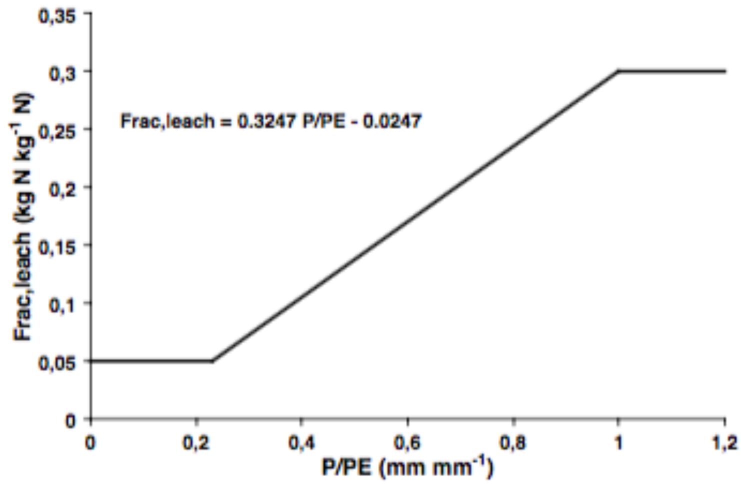

Figure 3: Fraction of N inputs that are lost by leaching and runoff (Frac, leach) as a function of the ratio of precipitation to potential evapotranspiration ratio (P/PE). From Rochette et al. (2008b)

The role of climate is not unique to Canada. A meta-analysis of global N_2O emissions characterized the impact of climate on N_2O emissions potential (Charles et al., 2017). Total annual precipitation had a significant impact on N_2O emission factor and that was dependent on nitrogen source. The emissions associate with organic N sources increased by a factor of 5 when the total annual precipitation increased from less than 250 mm to from 500 – 1000 mm and decreased by a factor of 2 when precipitation exceeded 1000 mm (Charles et al., 2017; Table 1). The “sweet” spot for N_2O emissions is at intermediate water contents (Linn and Doran, 1984). At low moisture contents oxygen supply limits denitrification, at high moisture content slow diffusion of gases limits oxygen availability and prevents the release of nitrous oxide promoting denitrification and N_2 as the primary product, resulting in reduced N_2O emissions from the soil.

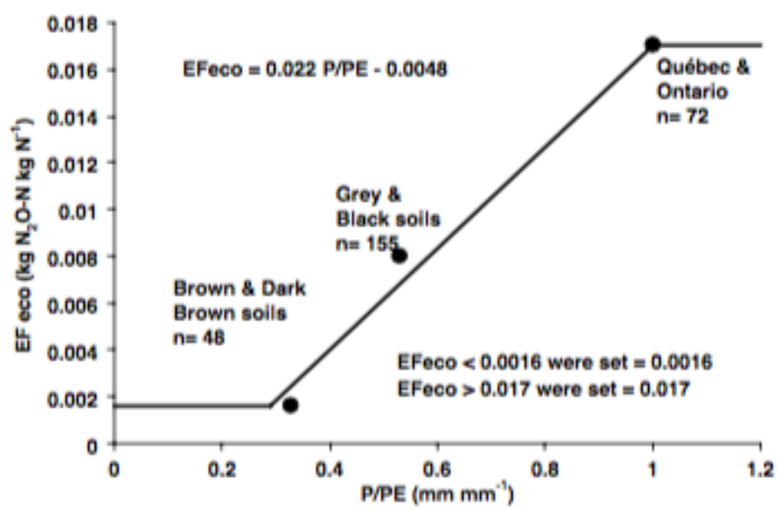

Figure 4: Relationship between the regional fertilizer-induced N_2O emission factor (EFreg) determined in three regions of Canada and the ratio of precipitation to potential evapotranspiration (P/PE). From Rochette et al. (2008b)

The impact of 4R management practices on N_2O emissions reduction is often related to soil water content. In a study of N fertilization of barley across soil zones Kryzanowski (2018) found regional influences of N fertilizer management changes on the N_2O emissions corresponded to soil zone which is a function of climate. van Kessel et al. (2013) noted that climate was an important factor influencing N_2O emissions in reduced tillage systems.

Table 1: The impact of climate, cropping system, soil management and soil properties on N_2O emission factors for soil amended with organic (FertiType O), synthetic (FertiType S) and combinations of organic and synthetic (FertiType O and OS) nitrogen sources (From Charles et al. 2017).

	FertiType O				—	**FertiType O and OS**					**FertiType S**				
	n	Raw mean	*Pr* > *F* mean	df (sem)		n	Raw mean	*Pr* > *F* mean	df (sem)		n	Raw mean	*Pr* > *F* mean	df (sem)	
Climate															
Climate type[1]	251	0.81	ns	197		323	0.96	ns	249		99	1.34	ns	68	
TAP[2], (mm)	229	0.80	***	173		296	0.97	***	221		91	1.37	ns	58	
0–250	42	0.20	0.21	(0.33)	*b*	51	0.21	0.29	(0.31)	*b*	12	0.48	–	–	
250–500	26	0.94	0.59	(0.47)	*ab*	45	0.78	0.61	(0.36)	*ab*	14	1.34	–	–	
500–1000	96	0.92	1.05	(0.18)	*a*	105	0.90	1.16	(0.21)	*a*	42	1.38	–	–	
>1000	65	0.96	0.50	(0.19)	*b*	95	1.54	0.63	(0.21)	*b*	23	1.83	–	–	
MAT[2], °C	167	0.82	ns	132		70	1.40	ns	170		70	1.40	ns	48	
Cropping Systems															
Land-use type	251	0.81	ns	196		323	0.96	ns	248		99	1.34	ns	67	
Crop type[3]	109	0.64	ns	87		116	0.65	ns	100		34	1.56	ns	67	
Soil Management															
Soil tillage	127	1.02	ns	100		184	1.20	ns	142		57	1.22	ns	35	
Incorporation[4]	207	0.72	ns	63		–	–	–	–	–	–	–	–	–	
Soil Properties															
Drainage	115	0.81	***	102		117	0.81	***	104		34	1.93	**	24	
Poor	49	1.10	1.02	(0.16)	*a*	49	1.11	1.02	(0.16)	*a*	15	3.70	5.34	(1.46)	*a*
Well	66	0.59	0.34	(0.03)	*b*	68	0.59	0.34	(0.03)	*b*	19	0.52	0.72	(0.13)	*b*
Texture	221	0.89	***	129		281	1.06	*	214		90	1.41	ns	61	
Fine	49	1.33	1.52	(0.38)	*a*	81	1.77	1.42	−0.26	*a*	24	3.01	2.85	(1.43)	*a*
Medium	44	0.96	0.82	(0.18)	*a*	56	0.91	0.71	−0.26	*b*	21	0.93	0.7	(1.86)	*a*
Coarse	128	0.67	0.49	(0.18)	*b*	144	0.73	0.59	−0.21	*b*	45	0.79	0.66	(3.00)	*a*
Organic C, (%)	193	0.8	**	151		252	0.96	**	194		86	1.03	***	59	
<1	31	0.64	0.47	(0.22)	*b*	56	0.61	0.44	(0.21)	*b*	20	0.71	1.09	(0.73)	b
1–3	105	0.83	0.48	(0.18)	*b*	116	0.80	0.46	(0.18)	*b*	35	0.78	−0.71	(0.66)	b
3–6	35	0.77	1.47	(0.29)	*a*	53	1.74	1.46	(0.26)	*a*	23	1.68	3.83	(0.72)	a
>6	22	0.84	0.72	(0.84)	*ab*	27	0.85	0.72	(0.84)	*ab*	8	1.07	1.21	(2.27)	ab
Nitrogen, (%)	165	0.88	**	140		225	1.04	***	177		81	1.04	ns	58	
<0.1	18	0.84	0.57	(0.35)	*b*	45	0.63	0.48	(0.22)	*b*	–	–	–	–	
0.1–0.2	117	0.72	0.50	(0.17)	*b*	124	0.72	1.69	(0.36)	*a*	–	–	–	–	
>0.2	30	1.54	1.66	(0.31)	*a*	56	2.08	0.59	(0.16)	*b*	–	–	–	–	
Soil C/N ratio	165	0.88	ns	140		229	1.04	***	178		85	1.12	**	61	
<10	18	0.85	0.66	(0.27)	*a*	41	0.54	0.81	(0.31)	*a*	19	1.11	1.40	(0.57)	*ab*
10–14	117	0.72	0.80	(0.19)	*a*	90	1.51	1.16	(0.23)	*a*	26	1.79	2.55	(0.71)	*a*
>14	30	1.54	0.55	(0.24)	*a*	98	0.83	−0.17	(0.27)	*b*	40	0.69	0.04	(0.49)	*b*
pH	184	0.87	1.76	ns		254	1.04	ns	194		90	1.13	ns	60	

[1]Climate types reported in the database: cool temperate dry/moist, tropical dry/moist, warm temperate dry/moist. [2]FertiType, type of fertilization: organic (O), synthetic fertilizers (S), organic and synthetic fertilizers (OS). [1]TAP, Total annual precipitation. [2]AMAT, Annual mean air temperature. [3]Crop type, type of crops (legume, grass, legume + grass) in grassland only. [4]Incorporation, incorporation depth (cm) of organic amendments only. n, total # of observations used in the analysis. *Pr* > F refers to a *F*-test used for comparing the soil factors of the total deviation.Df, degree of freedom. Significance of the effect: $Pr < 0.001$***, $Pr < 0.01$** and $Pr < 0.05$*, ns = non-significant.Means sharing a letter are not significantly different within soil factor by a LSD test ($P < 0.05$).

Soil Type

Soil characteristics influence the environment of the soil microorganisms that are producing N_2O. Relevant characteristics include soil physical characteristics (texture, bulk density) which influence the soil water content and aeration status; chemical characteristics (pH) which influence chemical speciation and the microbial environment; and biological characteristics (organic matter content, microbial community) which impact the nature and extent of microbial activity.

Soil Texture

Soil texture influences the water-holding capacity of the soil and therefore interacts with precipitation in influencing N_2O emissions. Rochette et al. (2018) examined the impact of soil texture on N_2O emissions from synthetic and organic N sources in Eastern Canada (Table 2). They found that emission factors increased in finer-textured soils. In addition, organic N sources had lower emission factors in coarse-textured soils but had emission factors that were equal to or greater than those for synthetic nitrogen sources in medium- and fine-textured soils.

Table 2: Effect of texture and fertilizer nitrogen type on soil nitrous oxide emissions factors in Eastern Canada (Rochette et al. 2018).

Region	Soil Texture	Synthetic N[a]	Organic N
		kg N_2O-N kg^{-1}N	
Eastern Canada	Coarse	0.0072 (0.0025) n = 19[b]	0.0028 (0.0007) n = 19
	Medium	0.0045 (0.0014) n = 19	0.0072 (0.0012) n = 15
	Fine	0.0304 (0.0108) n = 41	0.0276 (0.0065) n = 6

[a] Values in parenthesis are standard deviation.
[b] Number of observations associated with the mean is provided.

Nitrous Oxide Emissions Potential

The potential for N_2O emissions varies across these ecozones (Rochette et al., 2008a). The greatest annual emission rates occur in the Great Lakes/St. Lawrence Lowlands (Mixedwood Plains) associated with intensive corn-soybean Production. Drier regions and regions with lower intensity production result in lower N_2O emission potentials. In the Prairies, the drier climate results in nitrification becoming an important source of N_2O emissions. In the more humid regions denitrification, particularly associated with rainfall and snowmelt events is the dominant source of emissions (Risk et al., 2013; Rochette et al., 2018). In the regions with higher rainfall nitrate leaching and the indirect N_2O emissions associated with nitrate leaching become an important source of N_2O.

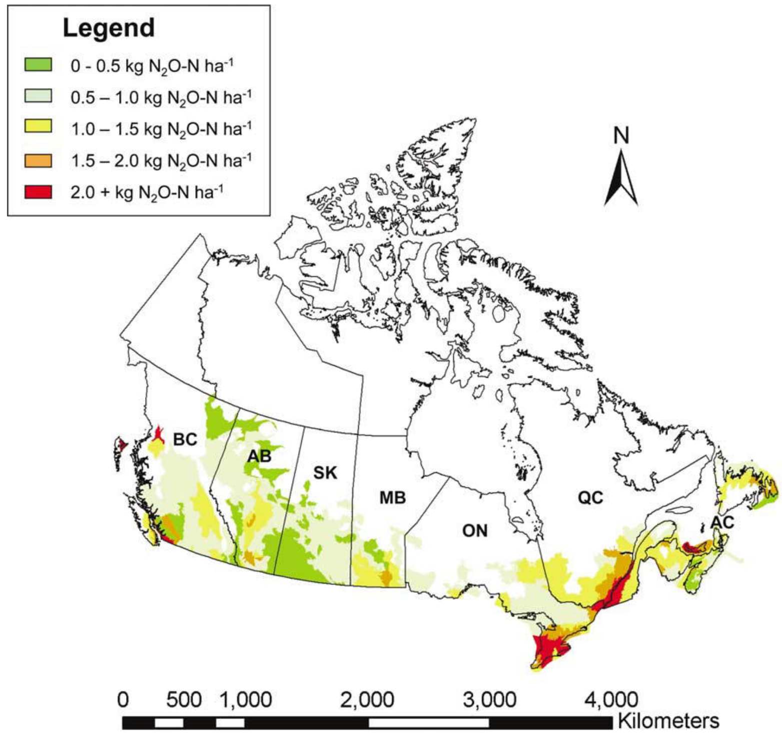

Figure 5: Annual N_2O emissions associated with agricultural production in Canada (Rochette et al. 2008a)

Tier I fertilizer-induced emission factor is 0.01 kg N_2O-N kg^{-1} fertilizer N (Bouwman et al., 2002). To reflect country-specific and regional influences on emission factors the IPCC permits the determination of Tier II coefficients (Rochette et al., 2008b). Tier II emissions factors are lower for the Prairies than for the more humid portions of the country (Table 3).

Table 3: Regional emission factors (EFreg) for the estimation of direct N_2O emissions. RFtill is the ratio factor accounting for the effect of tillage; RFtext is the ratio factor accounting for the effect of soil texture on emissions (from Rochette et al. 2008b).

Table 1. Emission and ratio factors for the estimation of direct soil N_2O emissions

Region	EFreg (kg N_2O-N kg^{-1} N)	Tillage	Soil texture	RFtill (±30%)	RFtext (±20%)
Prairies (Brown and Dark Brown)	0.0016	CT	All	1.0	1.0
	(± 25%)	MT+NT	All	0.8	1.0
Prairies (Black and Gray)	0.008	CT	All	1.0	1.0
	(± 25%)	MT+NT	All	0.8	1.0
Prairies (Other)	ND	All	All	1.0	1.0
Ontario-Quebec	0.017	CT	Fine	1.0	1.2
	(± 35%)		Medium	1.0	0.8
			Coarse	1.0	0.8
		MT+NT	Fine	1.1	1.2
			Medium	1.1	0.8
			Coarse	1.1	0.8
Atlantic Provinces	ND	CT	Fine	1.0	1.2
			Medium	1.0	0.8
			Coarse	1.0	0.8
		MT+NT	Fine	1.1	1.2
			Medium	1.1	0.8
			Coarse	1.1	0.8
British Columbia	ND	All	All	1.0	1.0

From: http://news.agropages.com/News/NewsDetail---19821.htm

Nitrogen source effects on N_2O emissions

Source selection provides the opportunity to use fertilizer N formulations that will result in lower N_2O emissions. Over the past two decades we have become aware that N_2O is generated from a number of combinations of nitrifying and denitrifying processes, specifically nitrifier nitrification, nitrifier denitrification, nitrifier-coupled denitrification, and denitrification of fertilizer nitrate sources (Fig. 6). These pathways include oxidative processes that occur primarily under aerobic conditions (nitrification) and reductive processes under conditions of oxygen limitation (denitrification). Despite this diversity of processes potentially producing N_2O, denitrification is generally considered the process that generates the greatest amount of N_2O because of its predominance during rewetting and thawing events and because of the relative yield of N_2O from denitrification (Risk et al. 2013; Rochette et al. 2018).

Aerobic pathways involve the oxidation of NH_4^+ and anaerobic pathways involve the reduction of NO_3^-. Further, NO_2^- and NO_3^- are anions which can be much more rapidly leached from soils during periods of water movement and involved in in direct pathways of N_2O production.

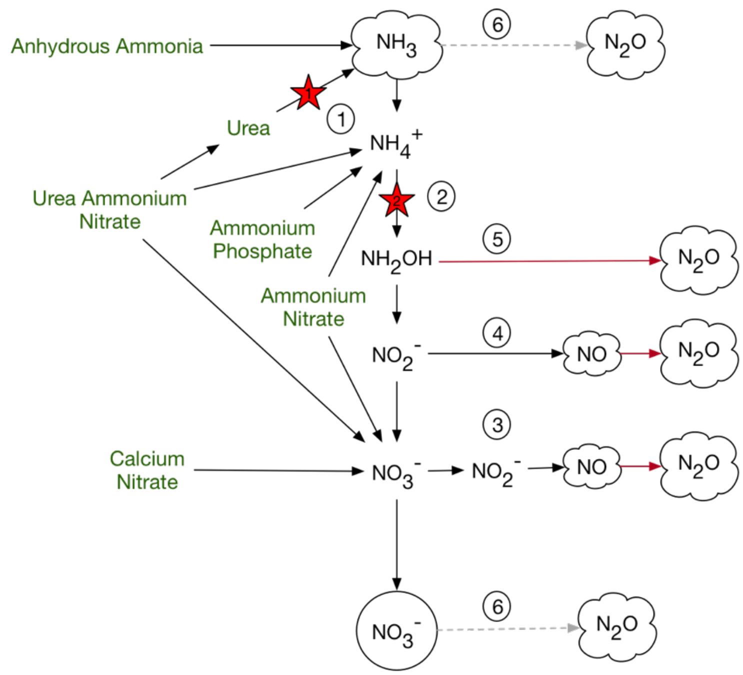

Figure 6: Pathways from fertilizer products (in green) to microbial N_2O production in soil. 1) Urea hydrolysis, 2) nitrification, 3) denitrification, 4) nitrifier denitrification, 5) nitrifier nitrification, 6) in direct N_2O emissions associated with NH_3 and NO_3 loss to the environment. The red stars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

While multiple pathways can result in N_2O production the majority originate from oxidized forms (NO_2^- or NO_3^-) and are associated with reductive processes during periods of high water content such as rainfall or snowmelt (Risk et al. 2013; Rochette et al. 2018). As a result, fertilizer N sources that do not contain NO_3^- and delay the formation of NO_3^- generally result in reduced amounts of N_2O emissions.

Form of nitrogen

Generally, there is less direct N_2O production from microbial processes involving NH_4^+ than those involving oxides of nitrogen (NO_2^- + NO_3^-). Over time, the predominant fate of ammonium is its oxidation to NO_3^- during nitrification. One of the major approaches to limiting N_2O production in soil is to delay nitrification to limit the duration of NO_3^- accumulation and thereby reduce the risk of N_2O emissions (Rochette et al. 2018). Delaying NO_3^- production is particularly effective in situations where there is a high potential for denitrification following N fertilizer application such as periods of high soil moisture early in the growing season.

The use of ammonium-based fertilizers is advocated as part of the Basic level of the proposed 4R programs and represents the majority of N fertilizer used in Canada (Fig. 8; Statistics Canada, 2018). The use of nitrate-based fertilizers (calcium nitrate, potassium nitrate) and in fertilizers containing nitrate in addition to other N forms (ammonium nitrate, calcium ammonium nitrate and UAN) represent less than 10% of the total N fertilizer sold (Fig. 8).

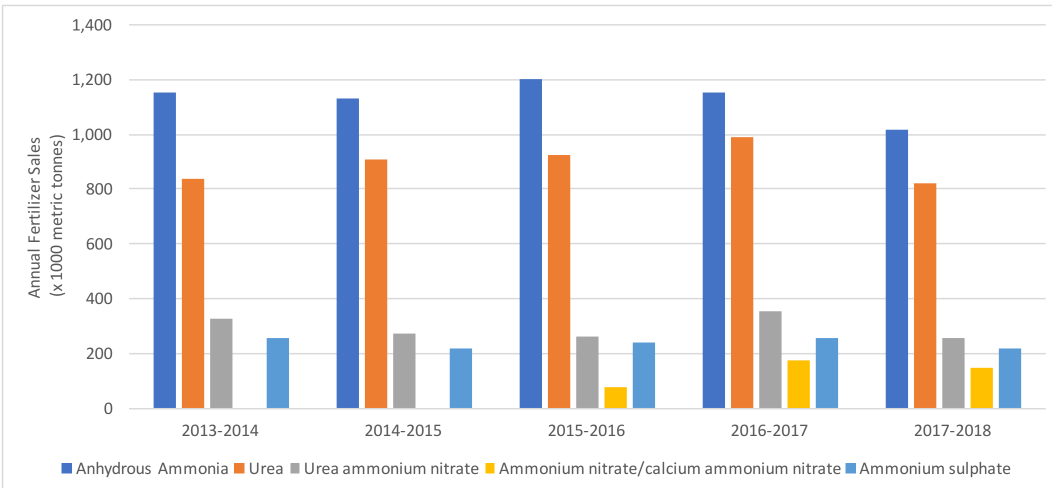

Figure 7: Forms of fertilizer nitrogen sold in Canada from 2013 to 2018. (Statistics Canada, 2018)

Studies examining the influence of nitrogen source on N_2O emissions have produced variable results. In a meta-analysis of corn cropping systems in the US Midwest, Ontario and Quebec, (Decock, 2014) report that source impacted fertilizer induced emissions and were ranked in the order anhydrous ammonia > UAN > ammonium nitrate > urea in terms of greatest to least N_2O emissions (Fig. 8). Vyn et al. (2016) also reported on studies examining N_2O emissions associated with various N sources being used in rainfed and irrigated corn production in the American mid-west and Ontario and Quebec. In contrast to Decock, they found emission coefficeints associated with UAN exceeded anhydrous ammonia and urea (Fig. 9). Abalos et al. (2016b) in examining 200 pair-wise observations from 23 studies from the same general region (US Mid-west and Eastern

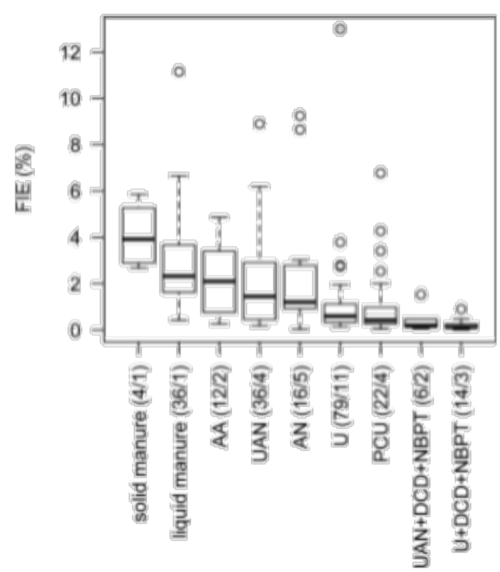

Figure 8: Influence of N source on fertilizer induced emissions (FIE) of N_2O. Numbers in parentheses indicate the number of observations on which the analysis was based, and the number of different field site from which observations originated (Decock, 2014).

Canada) found no significant effect of N source (urea vs. ammonium nitrate or UAN) or time of application (fall vs. spring) on N_2O emissions (Fig. 10).

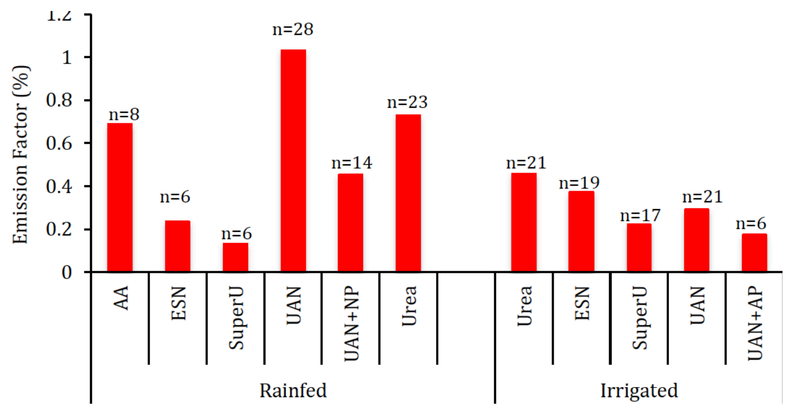

Figure 9: Fertilizer-induced emission factor due to sources under rainfed and irrigated corn systems. From Vyn et al. 2016

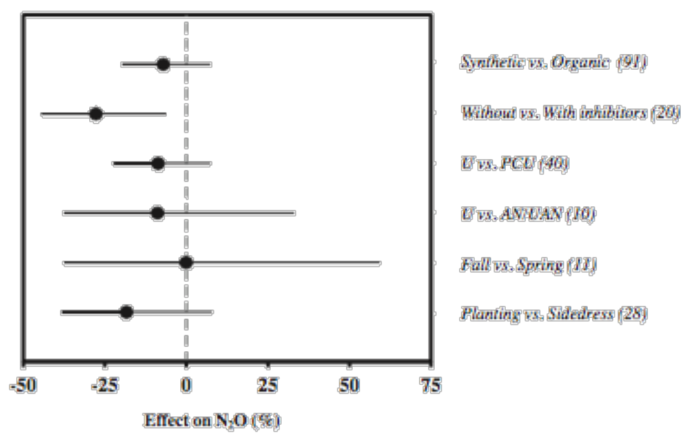

Figure 10: Influence of fertilizer management practices on N_2O emissions indicating mean effect and 95% confidence intervals. Number in parentheses indicate the number of control-treatment pairs. From Abalos et al. 2016.

In a meta-analysis of 27 studies, Eagle et al. (2017) reported that nitrification inhibitors, side-dress timing, and broadcast placement of fertilizer N had much more significant impacts on N_2O emissions than did modest (10%) rate decreases in rate of N application, reducing average losses by between 23 and 31%.

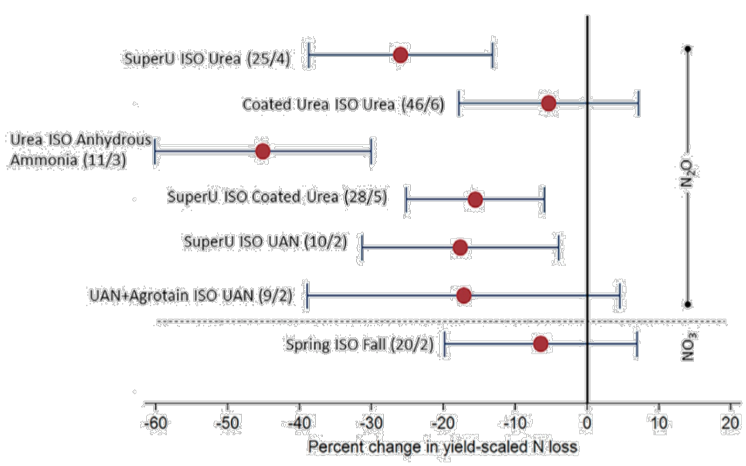

Figure 11: Effect sizes of N_2O and NO_3 losses from selected fertilizer management treatments, yield-scaled percent change with 95% confidence intervals. ISO = "Instead of" and values in parentheses are (number of comparisons / number of locations). from Eagle et al. (2017)

Enhance Efficiency Fertilizers

Emerging enhanced efficiency technologies have the promise for significant and reliable reductions in N_2O emissions. The term enhanced efficiency fertilizer (EEF) refer to a range of technologies that use inhibitors or coatings to influence the rate of nitrate appearance in soil (Table 4). The following definitions are being used in this paper:

> *Stabilized N – Stabilized nitrogen sources include urease inhibitors that inhibit enzymes in the soil which hydrolyze urea to yield ammonium (e.g. Agrotain, Limus, NYieldCX), nitrification inhibitors which inhibit ammonia-oxidizing bacteria, thereby delaying oxidation of NH_4^+ to NO_3^- (e.g. eNtrench, NBound, N-Serve) and double inhibitors (e.g. SuperU, NEON Air)*
>
> *Controlled Release – A controlled-release fertiliser is a granulated form of urea that releases nutrients gradually into the soil based on conditions such as moisture and temperature (i.e., release of urea dependent on soil conditions). An example of controlled release products is polymer coated urea, also called PCUs (e.g. ESN). The polymer membrane allows moisture to diffuse into the granule creating a solution of urea. The solution moves out through the membrane at a rate that is controlled by soil temperature.*
>
> *Slow Release - A slow-release fertilizer releases nutrients to plants slowly over time. Slow-release fertilizers are usually dry blends or granular formulas (e.g. sulfur-coated urea, methylene urea, isobuylidene diurea, urea formaldehyde and urea triazone). These formulations of urea reduce the solubility and release of urea.*

Enhanced efficiency fertilizers (EFFs) have been shown to result in relatively consistent reductions in N_2O emissions (Drury et al. 2012; Decock 2014; Thapa et al., 2016; Vyn et al. 2016; Drury 201; Snyder, 2017; Eagle et al., 2017). The magnitude of the reduction is influenced by the mode of action, soil and management factors.

Table 4: Examples of enhanced efficiency fertilizer products (From: http://news.agropages.com/News/NewsDetail---19821.htm)

Technique categories	Application objects	Specific techniques	Technical principle
Slow /control-released technology	Amide nitrogen, Ammonium nitrogen	PCU / SCU / PCSCU / NCU	Slow or control the rate of nitrogen release into the soil solution by physical coating on the surface of urea
		MU / IBDU / UF / CDU	Slow down the decomposition rate of urea in the soil by Chemical condensation reaction between urea and aldehyde
		Chelate urea by organic matters.	Chelate urea by organic matters like humic acid to slow down the decomposition rate of chelate urea in the soil
Urease inhibitor technology	Amide nitrogen	NPBT / NPPT	Slow down the reaction rate of urea decomposition into ammonium nitrogen by inhibiting the activity of urease in the soil.
Nitrification inhibitor technology	Amide nitrogen, Ammonium nitrogen	DCD / DMPP / Nitrapyrin	Slow down the conversion rate of ammonium nitrogen to nitrate nitrogen by inhibiting the activity of the nitrification bacteria in the soil.

In a meta-analysis of 113 data sets from 35 studies globally (Fig. 12), Akiyama et al. (2010) report an average reduction in N_2O emissions of 38% and 35% from inhibitor treated products and polymer coated products, respectively.

Similarly, in their global meta-analysis, Thapa et al., (2016) reported mean reductions in N_2O emissions as a result of the use of nitrification inhibitors of 38%, urease in combination with nitrification inhibitors of 30%, and controlled-release N fertilizers of 19% (Fig. 13).

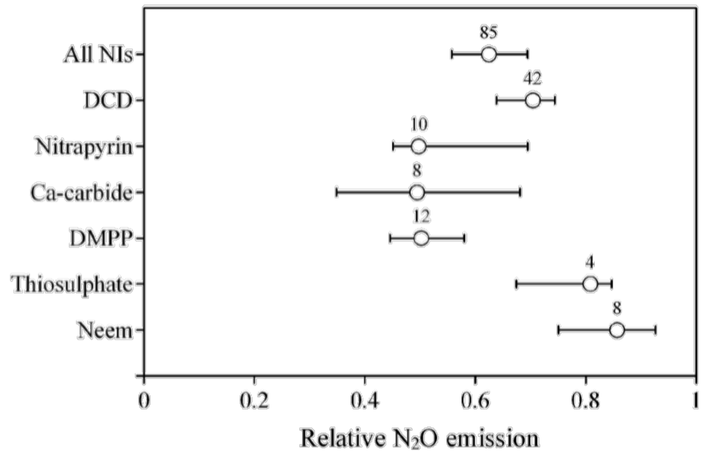

Figure 12: Influence of nitrification inhibitors on N_2O emissions relative to a conventional fertilizer (without nitrification inhibitor). Points indicate mean and bars indicate 95% confidence interval. Numbers indicate number of observations. From Akiyma et al. 2010.

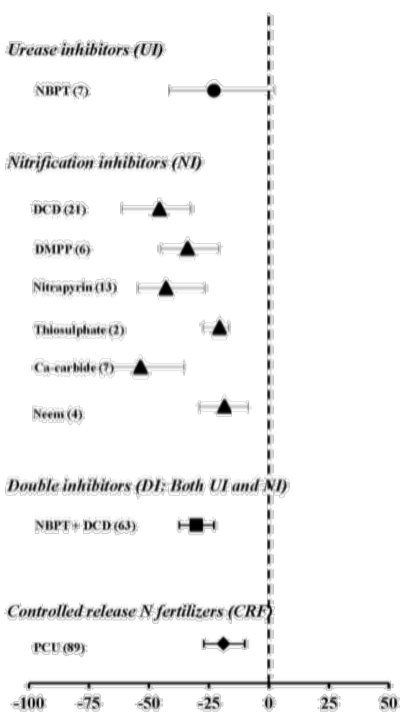

Figure 13: Effect of enhanced efficiency fertilizer products on N_2O emissions relative to conventional fertilizers. Points are means, bars indicate 95% confidence intervals. Number of studies reported in parenthesis. From Thapa et al. 2016.

Thapa et al. (2016) found nitrification inhibitors and controlled release products to give relatively consistent reduction of 25% to 50%, whereas urease was more variable resulting in 0 to 50% reductions (Fig. 13). Urease inhibitors alone are less effective in controlling N_2O emissions (Abalos et al., 2016b; Akiyama et al., 2010).

Snyder (2017) reports the influence of EEFs on direct N_2O emissions ranging from a 466 % increase to a 100% decrease. The majority of the reported reductions in N_2O emissions were between 25% and 50% as a result of the use of nitrification inhibitors. Urease inhibitors alone were found to have resulted in either increased N_2O emissions or only small reductions (Snyder 2017).

Thapa et al. (2016) examined the influence of crop type, pH, texture, mode of application, tillage and irrigation on the effectiveness of nitrification inhibitors, urease inhibitors, a combination of urease and nitrification inhibitors and controlled release products (Fig. 14). Nitrification inhibitors were most effective in corn-based systems and when used in banded fertilizer applications (Thapa et al., 2016). The use of nitrification inhibitors alone can result in increased loss of NH_3 (Drury et al., 2017; Snyder, 2017) and are generally less effective at reducing N_2O loss from alkaline soils as compared to neutral or acidic soils (Thapa et al. 2016).

The use of urease inhibitors in combination with nitrification inhibitors have been reported to result in greater reductions in N_2O emissions (Decock, 2014; Abalos et al. 2016b; Drury et al., 2017; Snyder, 2017), particularly in alkaline soils, when used in banded systems, coarse-textured soils or in irrigated systems (Thapa et al. 2016). Drury et al. (2017) noted that when ammonia volatilization was reduced by adding a urease inhibitor, N_2O emissions were increased by 30% when comparted to a nitrification inhibitor alone. They noted that by reducing pollution swapping (increased NH_3 loss to reduce N_2O loss), corn grain yields increased by 5% to 7%. The combination of a urease and a nitrification inhibitor resulted in increased yields of 19% compared with urea without the inhibitors. Wagner-Riddle (2017), in examining corn production systems in Ontario, observed significant reduction in N_2O emissions and NO_3^- loss when UAN+EEF was applied as side-dress in a wet year when emissions were large. Tenuta (2017) examined the potential for enhanced efficiency fertilizers in combination with fall N application to reduce N_2O emissions. They observed treatments with highest cumulative N_2O emissions were LIMUS (urease inhibitors), urea, ESN (coated urea) and anhydrous ammonia N-serve (nitrification inhibitor), with eNtrench (nitrification inhibitor) and SuperU (urease + nitrification inhibitor) resulting in lower emissions. Snyder (2017) reported more consistent reductions in direct N_2O emissions as a result of the use of dual urease and nitrification inhibitor combinations, falling in the range of 17% to 46% reduction in N_2O emissions. The addition of DCD to pig manure resulted in a 60% reduction in N_2O emissions in a corn-wheat system in Brazil (Aita et al., 2015).

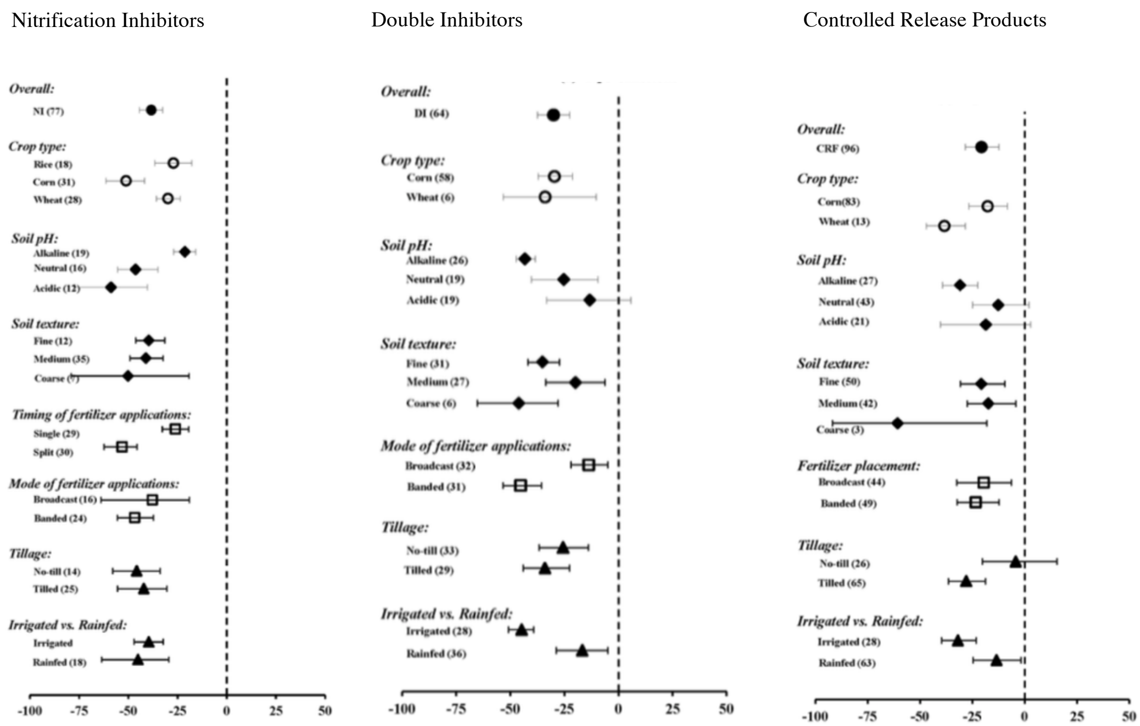

Figure 14: Effect of Nitrification inhibitors on N2O emissions as influenced by soil type and management system. (From Thapa et al. 2016)

Proposed guidance for NERP framework

Note that the guidance for the identification of emissions reduction modifiers is intended to be conservative. The following reflect generalizations that can be used to develop emissions reductions modifiers for various cropping systems in Canada.

The use of a nitrification inhibitor results in a reduction of approximately 35% in N_2O emissions compared to an uninhibited source.

A nitrous oxide emission reduction modifier should not be allocated to the use of urease inhibitors alone when using urea.

The use of both a urease inhibitor and a nitrification inhibitor results in a reduction of approximately 25% in N_2O emissions.

Controlled Release Products

Polymer-coated urea (PCU) has been less consistent than other EEFs in reducing N_2O emissions (Abalos et al. 2016b; Gao et al. 2017). Snyder (2017) reported a range of a 50% increase to a 70% decrease in direct N_2O emissions associated with the use of polymer coated fertilizer products across a range of studies globally. The majority of observations falling in the range of a 20% to 40% reduction in direct N_2O emissions (Snyder 2017). A single pre-plant application of PCU failed to reduce emissions compared to conventional granular urea, banding the PCU did however result in a 32% reduction in emissions (Gao et al. 2017). The use of PCU was found to result in a 15% decrease in N_2O emissions in no till barley production systems across a range of conditions in Alberta (Li et al., 2016). The reductions in N_2O were dependent upon rainfall conditions that created a risk of N_2O loss early in the growing season. Drury et al. (2012) found polymer coated urea only reduced N_2O emissions in 1 year out of 3 whereas it delayed but did not reduce N_2O emissions in the other 2 years. Polymer coated products were observed to be more effective in reducing N_2O emissions in moist soil conditions where there is a greater potential for N_2O loss via denitrification (Drury et al., 2012). The use of PCU resulted in increased N_2O emissions in potato production in Atlantic Canada (Zebarth et al., 2012). The authors noted that for enhanced efficiency products to deliver reduced N_2O emissions they may have to be applied at lower rates to reflect the increased efficiency of N delivery. Controlled release products were found to be more effective in wheat production, alkaline soils, under irrigation, tilled soils, and coarse-textured soils (Thapa et al. 2016). Kryzanowski (2018) found PCU could provide higher N use efficiency than uncoated urea, under similar conditions and resulted in a 5-6% reduction in N_2O emissions but noted that any disruption or reduction in crop N uptake during the growing season could result in higher emissions from PCU.

Proposed guidance for NERP framework

Note that the guidance for the identification of emissions reduction modifiers is intended to be conservative. The following reflect generalizations that can be used to develop emissions reductions modifiers for various cropping systems in Canada.

The use of polymer-coated urea results in a reduction of 10% in N_2O emissions.

Influence of Timing of N application on N_2O emissions

The objective of applying supplemental nitrogen fertilizers to crops is to meet the nitrogen requirements of the crop as efficiently as possible. Increasing nitrogen use efficiency (NUE) results in agronomic and environmental benefits. The challenge is to ensure there is sufficient nitrogen present while minimizing exposure to loss. (Robertson and Vitousek, 2009) conclude that asynchrony between the timing of N availability and crop N demand is probably the single greatest contributor to excess N and loss in annual cropping systems. Timing the supply of N to coincide with plant N demand minimizes the potential for N loss. Nitrate exposure, a temporally integrated measure of soil nitrate concentration (Burton et al., 2008), has been shown to be correlated with cumulative N_2O emissions across a range of ecozones and cropping systems (Aita et al., 2015; Chantigny et al., 2010; Engel et al., 2010; Gao et al., 2015; Maharjan and Venterea, 2013; Pelster et al., 2013). Management practices that reduce soil NO_3^- concentrations can decrease soil N_2O emissions (Aita et al., 2015)

Nitrogen losses occur primarily as a result of the leaching of nitrate, volatile losses of ammonia and the production of N_2O and N_2. The timing of these losses is a function of climatic conditions. The leaching of NO_3^- and the production of N_2O and N_2 are related to periods of high soil water content and therefore coincide with periods of rainfall and/or snow melt. Ammonia volatilization occurs as a result of the presence of NH_3 gas under alkaline conditions and its exchange with the atmosphere at the soil surface and therefore is enhanced in dry soils and during windy days or days in which there are high evaporative losses from the soil surface. Optimizing the delivery of nitrogen to the plant and minimizing N loss requires that the vulnerable forms of N are not present during the times of highest risk of loss. To minimize NO_3^- leaching and N_2O emissions the accumulation of NO_3^- should be avoided during periods of high rainfall or snowmelt. To minimized NH_3 loss NH_4^+ should not be allowed to accumulate in alkaline conditions at or near the soil surface.

In terms of timing of N application, it is useful to distinguish the more arid regions of Canada (prairies) from more humid regions of Canada. In Prairie Canada, the cold winters limit the potential for over-winter loss, making fall nitrogen application a viable alternative. In the more humid regions, fall N application would only be recommended for growing crops such winter cereals.

One of the challenges in examining processes that are so dependent on climate is that results vary from year-to-year as a result of fluctuations in weather patterns. Research on timing strategies almost always report year-to-year variation in results based on patterns of precipitation. For example, split application of fertilizer N has been observed to result in reduced N_2O emissions only when there is a potential for N_2O production in the early part of the growing season (Burton et al. 2008; Wagner-Riddle 2017; Farrell, 2017). These observations suggest risk-management based approaches are appropriate in assessing the role of timing in reducing N_2O emissions.

Nitrogen management practices which influence the timing of N supply include the *time of application*, the *splitting of application* and a host of *technologies that influence the rate of N release* in the soil following application.

Fall application of N - On the Prairies, the application of N fertilizers in the fall is a common practice. This is due to cost of N fertilizer products at that time as well as the opportunity to shift field operations from spring to fall. This usually involves an ammonium-based N source. In the more humid regions of Canada N fertilizer is seldom applied in the fall unless it is to a growing crop such as winter cereals.

The SDD (FISAF, 2015) concluded that "there is a considerable body of evidence demonstrating that in the cropping systems of the northern Great Plains in Canada, spring-applied N generally out performs fall (Malhi et al., 2001; Malhi and Nyborg, 1984). The ranking from most to least effective under conventional tillage can be summarized as spring banded > fall banded > spring broadcast > fall broadcast. Fall-application performs about equally well to spring application in drier regions under normal moisture conditions. Under wetter than normal conditions, overwinter losses of fall-applied nitrogen can occur.".

More recent studies have shown fall applications resulted in greater N_2O emissions (Kryzanowski, 2018), failed to detect a difference in spring vs fall applications (Abalos et al., 2016a), or found fall N applications to result in less N_2O loss than spring applications (Tenuta et al., 2016; Kryzanowski et al., 2018), particularly if N application occurs late in the fall after the soil has dropped below 5 °C (Tenuta et al., 2016). In a study of N fertilization of barley across soil zones in Alberta, Kryzanowski (2018) found spring application of nitrogen fertilizer was the most effective means of reducing total emissions. Switching from fall applied nitrogen fertilizer to spring application results in 17% to 25% reduction in N_2O emissions

Preventing the nitrification of NH_4^+ to NO_3^- prior to the winter period reduces the potential for N losses (Risk et al., 2013; Tenuta et al., 2016). This can be achieved by the delaying N application in late fall (Tenuta et al., 2016), sub-surface banding of NH_4^+-based fertilizers (Malhi et al., 2001), the use of nitrification inhibitors (Malhi and Nyborg, 1984), or the use of coated urea (Kryzanowski, 2018). Kryzanowski (2018) found that switching from fall applied urea to fall applied PCU results in 6% reduction in N_2O emissions. Like the results for EEFs, the results can vary from year-to-year. A Manitoba study of enhanced efficiency fertilizers for fall N applications found that N_2O emissions from all N addition treatments were higher for fall than spring addition in one year of study (2015) but not in the second year of study (2016) (Tenuta, 2017).

Proposed guidance for NERP framework
Note that the guidance for the identification of emissions reduction modifiers is intended to be conservative. The following reflect generalizations that can be used to develop emissions reductions modifiers for various cropping systems in Canada.

Delaying of fall application of N until the soil has cooled to below 10 °C or the use of an inhibitor will result in N being retained in the NH_4^+ form and a reduction of N_2O emissions of 30% relative to spring pre-plant application.

Spring application of N will result in a reduction of N_2O emissions of ~20% relative to an early fall application with no inhibitor.

The fall application of N should be avoided in the more humid regions of Canada (Abalos et al., 2016b) unless it is part of a P application or being applied to a winter cereal.

Split applications of N – Split applications of N involve the application of an initial amount of N early in the growing season (pre-plant or at planting) followed by application or applications later in the season closer to the period of maximum plant N demand. Split application will only result in reduced N_2O emissions in situations where there was a potential for N_2O loss over the time period of the split (Burton et al., 2008). Thus, the response to split application treatments can vary from year-to-year.

In a study of crop production in Minnesota, (Fernandez et al., 2016) observed split applications to emit 26% less N_2O than a single pre-plant application of urea with no differences in grain yield. (Drury et al., 2012) found that in conventional tillage treatments, N_2O emissions were 49% greater when N was applied at planting compared to a side-dress. Split application of urea N in a corn-soybean system do not always result in reduced N_2O emissions (Venterea and Coulter, 2015). In this study the failure of the split application to reduce N_2O emissions was attributed, in part, to a prolonged dry period prior to the split application followed by a period of heavy rainfall following the split. There was a significant relationship between cumulative N_2O emissions and nitrate exposure (referred to as nitrate-nitrite intensity) suggesting that the split application treatments resulted in increased availability of nitrate and nitrite to loss following application.

Splitting the application of pig manure in a corn-wheat production system in Brazil resulted in a 33% reduction in N_2O emissions (Aita et al., 2015). The combination of split application with the use of DCD resulted in a 41% reduction in N_2O emissions. The combination of split application and the use of DCD did not however result in as great an emissions reduction as did the use of DCD in a single application which resulted in a 60% reduction in N_2O emissions (Aita et al., 2015). Similarly, (Abalos et al., 2016b) observed that the combined adoption of split fertilizer application with inhibitors and a N fertilizer application rate 10% lower than the conventional application rate (i.e. 150 kg N ha^{-1}) resulted in reduced N_2O emissions, but the benefits were lower than those achieved with a single fertilizer application at sidedress. In a corn production system in Ontario, Wagner-Riddle (2017) did not observe a reduction in N_2O emissions as a result of split N application. A combination of UAN with inhibitors and split N application resulted in significant reduction in N_2O emissions, but only in the dry year when emissions were small (Wagner-Riddle 2017).

In examining potato production systems in Manitoba (Gao et al., 2017) found split urea application with N being added both at hilling and through fertigation, resulted in reduced N_2O emissions. A single split urea (2/3 pre-plant, 1/3 hilling) also reduced N_2O emissions compared to single pre-plant urea application. Similarly, (Burton et al., 2008) observed that split application reduced N_2O emissions by 30% in a year when there was rainfall between planting and the split application of N (hilling), but that there was no significant difference N_2O emissions in drier year where there was no risk of N loss during the period between planting and hilling. Farrell (2017) observed that in an irrigated canola production system split application (broadcast-incorporated) of urea resulted in lower cumulative N_2O emissions than those from plots receiving all the fertilizer during a single pre-plant application prior to seeding.

These examples illustrate that the success of 4R practices in reducing N_2O emissions are dependent on climatic conditions and the benefits of split application with other 4R practices may be, but are not necessarily, additive.

Proposed guidance for NERP framework

Note that the guidance for the identification of emissions reduction modifiers is intended to be conservative. The following reflect generalizations that can be used to develop emissions reductions modifiers for various cropping systems in Canada.

In-season split (1/3 or more) application of nitrogen fertilizer results in a 15% reduction in N_2O emissions.

Foliar application/Fertigation -
There is limited information on the impact of timing of N application on N_2O emissions in irrigated systems in Canada. Gao et al. (2017) found that split urea application at pre-plant and hilling and fertigation with in-season application of UAN resulted in lowest N_2O emissions relative to a single pre-plant urea application. Farrell (2017) observed that cumulative N_2O emissions in irrigated canola were significantly impacted by the timing of the fertilizer application. Emissions were lower for split N application compared to a single application at seeding.

Influence of N Placement on N_2O emissions

Nitrogen fertilizer placement attempts to place the fertilizer in an environment where its availability to the plant is maximized and the potential for N loss in minimized. Care must be exercised to ensure placement does result in toxicity to the plant. Often sub-surface placement has a positive impact on yield and therefore may reduce N_2O emissions intensity.

An important consideration in assessing placement effect is the potential for NH_3 loss. The SDD (FISAG, 2015) noted that "placing N fertilizer in bands also reduces volatilization losses, lowers the risk of immobilization, and slows the rate of nitrification of fertilizer N to nitrate in the fall, which reduces the risk of overwinter loss (Yadvinder-Singh et al., 1994)." The loss of NH_3 may result in reduced N_2O emissions as a result of the lower soil NH_4^+ content and subsequent NO_3^- production, this is not a desired trade-off from either a production or environmental stand point.

The SSD (2015) document made the following points:

- *Subsurface band placement tends to increase nitrogen use efficiency and more effectively increase yield than broadcasting nitrogen.*
- *Based on their meta-analysis of emission measurements from experiments comparing tillage and placement, Van Kessel, et al. (2013) concluded that deep placement (>5 cm) of nitrogen was an effective strategy for reducing emissions in no-tillage and reduced tillage systems.*
- *Banding urea can increase ammonia volatilization on dry acidic soils compared to surface placement (Rochette, et al., 2009) and ammonia losses contribute to indirect N_2O emissions.*

The impact of placement on N_2O emissions is influenced by soil water content. Sub-surface placement has been shown to increase N_2O emissions in sub-humid ecosystems (Venterea et al., 2010 (Engel et al., 2010; Fujinuma et al., 2011; Venterea et al., 2010), although this not observed in more arid settings (Gao et al., 2015; Farrell, 2017). Based on their experimental observations, Farrell (2017) conclude that wetter conditions were required to induce and maintain denitrification activity in the sub-surface band. Gao et al. (2015) reported that at two sites in Manitoba cumulative N_2O emissions were generally greater following broadcast/incorporation than side-banding. These differences may reflect differences in the timing of N application. Gao et al. (2017) observed that banding of ESN, but not urea, reduced N_2O emissions compared to broadcast-incorporation placement. Placement has also been shown to interact with the tillage system (van Kessel et al., 2013). N_2O emissions were increased in NT and RT systems in dry climates, and in particular in the first 10 years of reduced tillage and shallow (< 5 cm) N placements (van Kessel et al., 2013).

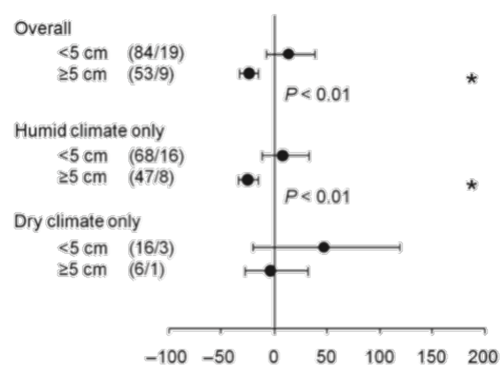

Figure 15: Influence of NT and RT as compared to conventional tillage on area-scaled N_2O emissions as influenced by depth of fertilizer N placement and climate (from van Kessel et al. 2013).

Depth of placement may also be a factor in determining the extent of N_2O emissions. (Drury et al., 2006) observed that deeper placement of N generally results in greater N_2O emissions, whereas van Kessel et al. (2013) found that when fertilizer-N was placed at >5 cm depth, in reduced tillage systems, significant reductions were observed in area-scaled N_2O emissions, in particular under humid climatic conditions.

Placement of fertilizer products also has the potential to influence the rate of solubilization and/or nitrification of ammonium-based N sources and may result in reduced N_2O emissions.

Proposed guidance for NERP framework

Note that the guidance for the identification of emissions reduction modifiers is intended to be conservative. The following reflect generalizations that can be used to develop emissions reductions modifiers for various cropping systems in Canada.

In sub-humid regions, surface dribble banding of UAN should be avoided.

Compared to spring broadcast, fall banding of nitrogen fertilizer is equivalent in N_2O emissions.

Impact of fertilizer N application rate on N_2O emissions

IPCC National accounting frameworks directly reflect the impact of the rate of N fertilizer application on N_2O emissions by expressing emissions as the product of fertilizer N rate and an emission factor. The influence of the other three "Rs" is represented in changes in the magnitude of the emission factor using an emission factor modifier. Implicit in this approach is the assumptions that N_2O emissions are a linear function of fertilizer N rate (i.e., a single emission factor applies across all rates) and that other sources of N do not influence the magnitude of fertilizer N induced emissions. Both assumptions are incorrect. Firstly, the relationship between N fertilizer application rate and N_2O emissions is not linear (Fig. 16). Secondly, N_2O emissions occur not only from fertilizer N sources, but are a function of total soil N supply derived from multiple sources. Thus, the magnitude of the non-fertilizer N sources influences the magnitude of fertilizer N induced N_2O emissions.

Fertilizer N application rate is also a particularly important "R" in that the yield response to N fertilizer application rate is one of the fundamental factors managed in developing best agronomic production practices for a crop. Producers are keenly aware of N application rates and their implication for potential yields. Often the choice of an N rate is seen primarily through an economic lens. The maximum economic rate of N is the rate at which the value of the next increment in crop yield exceeds the cost of the fertilizer. The maximum economic rate of N does not explicitly reflect desired N recovery efficiency (Fig. 16) or the potential for environmental impact. The use of additional "insurance" N to ensure increased yields should climatic conditions be favourable result in N additions in excess of the maximum economic rate of N.

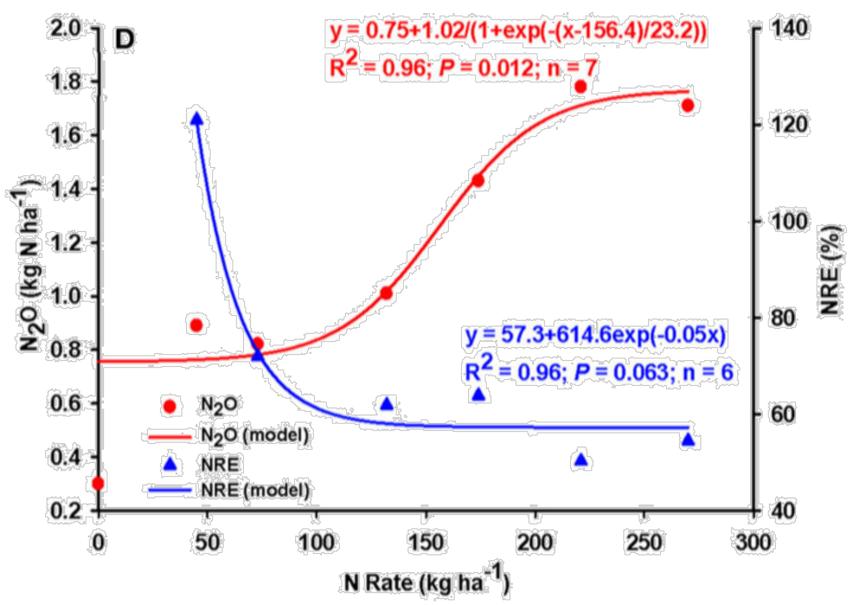

Figure 16: Relationship between fertilizer N application rate (N Rate, kg N ha-1) and cumulative growing season N2O emissions (N2O, kg N ha-1) and nitrogen recovery efficiency (NRE, %) defined as the total increase in above ground N uptake by the plant as a result of N fertilizer application. From Omonode et al. 2017.

In a meta-analysis of 597 pair-wise comparisons, Han et al. (2017) found that the rate of N application was more significant driver of N_2O emissions than was N source. They observed that applying N fertilizer at higher than recommended rates resulted in 55% greater N_2O emissions than application at the recommended rate and that application at less than recommended rate resulting in a 33% decline in N_2O emissions (Fig. 17). In a study of N fertilization of barley across soil zones Kryzanowski (2018), found reduction in emissions was greater for high N treatments compared to low N. Eagle et al. (2017) concluded that lower fertilizer N rates resulted in lower N_2O emissions and NO_3^- leaching. Cutting typical N fertilizer rates by as little as 10 kg N ha^{-1}, a rate likely to be considered reasonable by producers, reduced average N_2O emissions by 4% and reduced average NO_3^- leaching losses by 2.9% under average conditions.

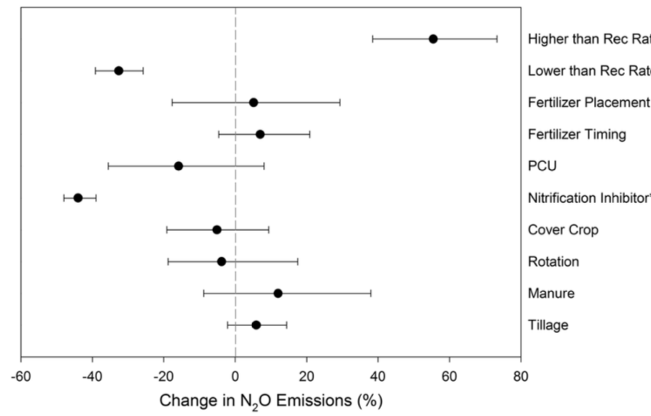

Figure 17: Effect of management practices on area-scaled N_2O emissions reported as percent change from the control. Mean values and 95% confidence intervals of the back- transformed response ratios are shown. The result for nitrification inhibitors was from Qiao et al. (2015) and was shown for comparison. From Han et al., 2017.

There have been calls for alternate measures of agronomic, economic, and environment soundness of N management systems (Snyder et al., 2014). (Omonode et al., 2017) assessed whether the impact of fertilizer N rate might better be quantified in terms of various measures of N uptake by the plant and/or residual N in the soil. Residual soil nitrate, nitrate remaining in the soil following crop harvest is also used in Agriculture and Agri-Food Canada's Agri-Environmental Indicators as an indicator risk of water contamination by nitrogen (Clearwater et al. 2016). (Omonode et al., 2017) found measures of N uptake by the plant and/or residual N in the soil were highly correlated with area scaled N_2O emissions. They noted that as fertilizer N rate increased, there was a non-linear response in growing season N_2O emissions and decline in N recovery efficiency (NRE) by the plant (Fig. 16). Growing season N_2O emissions increased exponentially when plant N recover dropped below 60%.

To fully realize potential reductions in N_2O emissions, increased nitrogen use efficiency resulting from the implementation of 4R practices should result in a corresponding reduction in the optimal rate of N fertilizer and thereby a reduction in N_2O emissions (Zebarth et al. 2012; Rose et al. 2018). Often experimental designs consider various candidate 4R practices at the same rate of N fertilizer addition and as a result may not reflect the opportunity to reduce rate and N_2O emissions while maintaining yield. (Rose et al., 2018) noted that studies examining enhanced efficiency products often find decreased N_2O emissions but no significant effect on yield. They argue that reduced N fertilizer rates should be considered to reflect the enhanced efficiency.

Non 4R factors that influence N_2O emissions

While the 4R program focuses on the opportunities for fertilizer management to reduce N_2O emissions, it is important to recognize the implications of other management factors and soil conditions can influence the success of fertilizer management in reducing N_2O emissions. These factors primarily act by altering the availability of carbon and/or the soil aeration as influenced by water content.

Soil Type/Texture

In their global meta-analysis, Charles et al. (2018) identified the significance of a range of soil factors in influencing N_2O emissions from both organic and inorganic fertilizers (Table 1). For both mineral and organic fertilizers, Charles et al. (2018) found poorly drained soils had greater emissions factors than did well-drained soils.

For mineral fertilizers (FertiTyp S), the factors resulting in the greatest increases in N_2O emission factor were the result of difference in drainage (poor > well drained) and organic matter content (N_2O emissions were greater in soils with >3% organic C) and soils with wide C:N ratios (>14) had reduced N_2O emissions. While N_2O emission factors from fine textured soil were numerically greater than from medium or coarse textures, these differences were not statistically different (Table 1). For organic fertilizers (FertiType O) drainage (poor > well drained) and texture (fine = medium > coarse) were significant influences as were organic C content (3% or less < 3-6% = greater than 6%) and nitrogen content (0.2% or greater > 0.2 % or lower; Table 1).

Abalos et al. (2016b) identified soil texture and C:N ratio as the dominant factors influencing N_2O emission factors. Fine-textured soils were highly responsive to fertilizer management in in terms of both N_2O emissions and crop yield. The mitigation of N_2O emissions without concurrent yield reductions is most frequently achieved in soils with a low C/N ratio (i.e. <12.5).

Proposed guidance for NERP framework

Poorly drained soils should be considered as higher risk areas for N_2O emissions.

Irrigation and Drainage

Tile drainage reduced N_2O emissions during periods of excess moisture, but not in periods of adequate precipitation in a corn production system in Minnesota (Fernandez et al., 2016). Averaged across years, the undrained soil emitted 1.8 times more N_2O than the drained soil. Elmi et al. (2005) found denitrification ($N_2O + N_2$) to be greater under sub-irrigation (12.9 kg N ha^{-1}) than in freely drained systems (5.8 kg N ha^{-1}). The N_2O emissions were greater under freely drained systems (2.2 kg N ha^{-1}) than sub-irrigation (1.6 kg N ha^{-1}). The reduced N_2O production under sub-irrigation was attributed to a greater reduction of N_2O to N_2. Nangia et al. (2013) reported that while there were no statistically significant differences in observed N_2O fluxes between conventional tile drainage and controlled tile drainage fields during the growing season. They report that predicted N_2O fluxes, using a semi-empirical model (NEMIS-NOE), were higher for conventional tile drainage for approximately 70% of the paired-field study periods. Thus, while tile drainage appears to reduce emissions during periods of excess moisture, it is not clear that tile drained systems consistently emit lower amounts of N_2O emissions. Controlled drainage water management has the potential to reduce N_2O emissions, but this appears to be the result of creating conditions conducive to complete denitrification to N_2.

Vyn et al. (2016) found that fertilizer-induced emissions were greater under rainfed (0.73%) compared to irrigated corn (0.41%) systems in a meta-analysis of the US corn belt and Eastern Canada. Applying reduced deficit irrigation and the nitrification inhibitor DMPP individually slightly decreased N_2O emissions but when applied in combination resulted in a greater reduction in N_2O emissions (Jamali et al., 2016). In isolation, DMPP tended to be more efficient than optimised irrigation management in mitigating N_2O emissions.

Tillage

In the drier regions of the country, greater N_2O emissions are generally observed under conventional tillage than reduced tillage management due to higher rates of nitrification (Helgason et al., 2005; Kariyapperuma et al., 2011). In contrast, in the more humid regions of Canada greater N_2O emissions usually occur under reduced tillage due to wetter soil conditions resulting in higher rates of denitrification (Rochette et al., 2008b; Smith et al., 2010). Drury et al. (2012) observed greater N_2O emissions (4.2 kg N ha^{-1}) under conventional tillage than under no till (3.5 kg N ha^{-1}) or zero till management (2.4 kg N ha^{-1}). Uzoma et al. (2015) observed no difference between tillage treatments in a study conducted in the Red River Valley, during a period of moderate precipitation. In a meta-analysis considering 239 direct comparisons between conventional tillage (CT) and no tillage (NT) or reduced tillage (RT), van Kessel et al. (2013) did not observe a significant impact of tillage system on N_2O emissions (Fig. 18). They noted that in long-term sites (<10 years) in dry climates, NT/RT reduced N_2O emissions by 27%. In sites under NT/RT for reduced durations N_2O emissions were 57% greater than from CT counterparts.

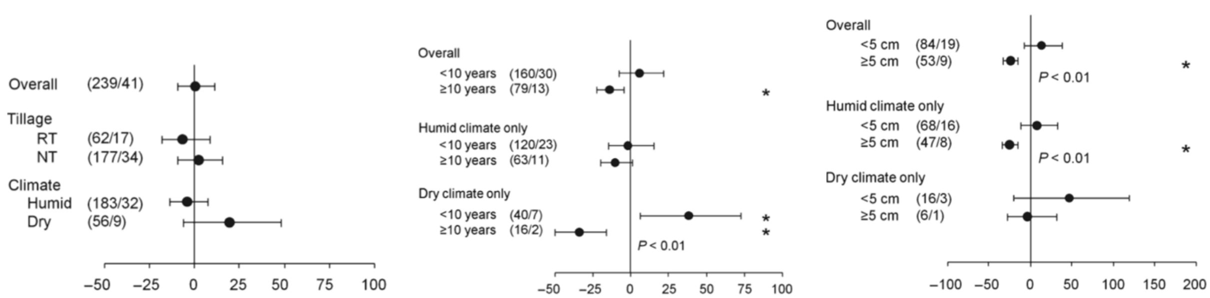

Figure 18: Effect of no till (NT) and reduced tillage (RT) relative to conventional tillage (%) on cumulative growing season N_2O emission (kg N ha^{-1}) broken out according to climate, duration of tillage treatment and depth of tillage. from van Kessel et al. (2013)

Crop rotation/cropping system

Including Legumes in Rotation – Reflecting the role of legumes in rotation in N_2O emissions historically has been complicated by apparent double accounting – emissions associated with the process of biological N fixation and emissions associated with N-rich residue decomposition. This issue has since been resolved (Rochette and Janzen, 2005). They note that there is little evidence for the use of an emission factor for biological N fixation (BNF) by legume crops equal to that for fertiliser N. Increased N_2O emissions in legume crops may result from the N release from root exudates during the growing season and from decomposition of crop residues after harvest. As a result of this work N_2O emissions induced by the growth of legume crops are estimated solely as a function of crop residue decomposition using estimated of above- and below-ground residue inputs.

Drury et al. (2014) found that growing corn in a corn-oat-alfalfa-alfalfa rotation lost 6.5 kg N ha^{-1}, 12% lower than emission under continuous corn cropping (7.3 kg N ha^{-1}) despite the higher N input from fertilizer and legume N sources. Long-term management practices and crop rotation were attributed for the difference. Uzoma et al. (2015) observed that N_2O emissions were more than 4 times higher under annual cropping than under alfalfa production. The plow down of alfalfa did not result in any significant emission events in either the fall or winter. Large emissions were observed in the year following alfalfa incorporation despite their being only moderate amounts of additional N fertilizer application. This consistent with the findings of Wagner- Riddle et al. (1997), they also measured high N_2O emissions in the spring following the plow down of alfalfa the previous autumn. Rochette et al. (2004) found that despite consistently higher soil N, N_2O emissions were greater under alfalfa than timothy production in only 6 out of 10 field comparisons. Giweta et al. (2017) found that extended rotations involving legumes (with or without manure) resulted in greater N_2O emissions than a wheat-fallow rotation. Further they found that in this long-term rotation experiment, N_2O emissions were correlated with total soil N (Fig. 19). The rotation that did not contain a legume tended to have reduced total soil N and reduced N_2O emissions. Manure addition increased total soil N and N_2O emissions.

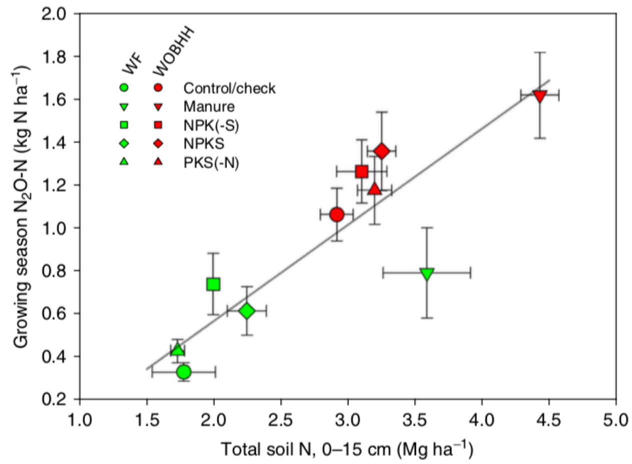

Figure 19: Relationship between cumulative growing season N_2O emissions and total soil N (0-15 cm) of soils with different fertilization histories under wheat-fallow (WF) and wheat-oat-barley-alfalfa/brome hay- alfalfa/brome hay (WOBHH) crop rotations at Breton Plots, Western Canada. Symbols represent mean values, and error bars represent 1 standard error. The line represents the orthogonal regression relationship $y = 0.45\ x – 0.33$. The slope is significantly different from zero ($p<0.001$), but intercept is not ($p = 0.21$). From Giweta et al. (2017).

In a study of the interaction of manure application and cropping system, (Nikiema et al., 2016) found that over two growing seasons and across manure types, the N_2O emissions factor did not differ between annual cropping and perennial forage systems.

Cover Crops - In a meta-analysis examining the role of cover crops in N_2O emissions, Han et al. 2017 found that cover crops reduced N_2O emissions by 58% relative to bare soils, but that the additional N supplied by the cover crop resulted in increased emissions in the subsequent crop (Fig. 20). The magnitude of N_2O emissions associated with the cover crop was inversely related to C:N ratio of the cover crop (Fig. 21). Han et al. (2017) note that in most of the comparisons examined, the fertilizer N rate was not adjusted to reflect the additional N contribution of the cover crop.

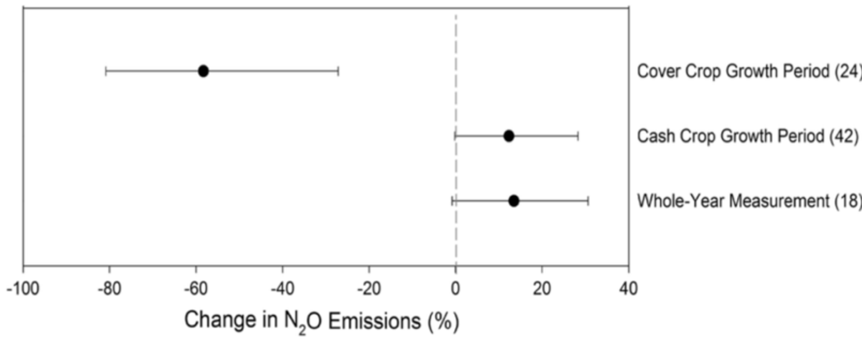

Figure 20: Effect of cover crops on area-scaled N_2O emissions depending on different measurement periods. Mean values and 95% confidence intervals of the back-transformed response ratios are shown. From Han et al. (2017).

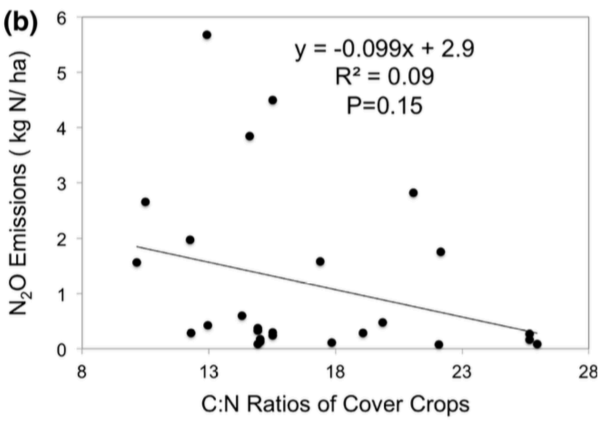

Figure 21: Relationship between N_2O emissions and cover crop C:N ratios (n = 27). From Han et al. (2017)

Cropping System and N Use Efficiency - Understanding the influence of the inclusion of legumes in rotation is complicated by the different ways the N associated with the legume are considered in choosing the rate of N fertilizer to be applied. Rochette et al. (2018) found that in land receiving animal manure, perennial cropping systems had N_2O emissions that were 28% of those of annual cropping systems. This was attributed to the efficiency of N cycling in perennial cropping systems.

Table 5: Effect of crop type and fertilizer nitrogen type on soil nitrous oxide emission factors in Eastern Canada. From Rochette et al. (2018).

Region	Crop Type	Synthetic N[a] kg N_2ON kg^{-1}N	Organic N
Eastern Canada	Annual Crop	0.0211 (0.0092) n = 61[b]	0.0177 (0.0064) n = 10
	Perennial Crop	0.0041 (0.0013) n = 18	0.0044 (0.0011) n = 30

[a] Values in parenthesis are standard deviation.
[b] Number of observations associated with the mean is provided.

A study conducted in Minnesota found that corn stover removal decreased soil total CO_2 and N_2O emissions by 4 and 7 %, respectively, relative to no removal. Lower GHG emissions in stover removal treatments were attributed to decreased C and N inputs into soils, as well as possible microclimatic differences associated with changes in soil cover (Jin et al., 2014).

Thomas et al. (2017) found that cover crops (fall rye, oilseed radish) increased non-growing season N_2O emissions. Winter N_2O emissions were greater than spring or fall emissions. In one of the two years studied the magnitude of non-growing season N_2O losses were correlated with late-fall soil NO_3^- concentration, with concentrations of < 6 mg N kg^{-1} soil limiting N_2O emissions, in the second year N_2O emissions were correlated with water extractable organic carbon.

Conclusions

There is now a considerable body of scientific evidence supporting the ability of 4R N fertilizer management to reduce N_2O emissions in Canada. It is clear that developing a 4R program is, at the very least, region and crop specific and, in many cases, site-specific. The overall program must consider the interaction of source, rate, time and place.

The impact of N fertilizer management on N_2O emissions is highly dependent on climate and soil type. In the prairie region of Canada, more arid conditions result in lower N_2O emissions and cause in season precipitation to be a major factor influencing the potential for N_2O emissions. Cold winter conditions result in lower losses during the non-growing period. In contrast the more humid regions of Canada, the timing of precipitation remains an important determinant of the potential for N_2O loss, but more open winters result in greater non-growing season emissions. In these regions reducing fall nitrate accumulation is an important strategy in reducing N_2O emissions and fall N applications should be avoided.

Fertilizer products/practices that delay the formation of nitrate are consistent in their ability to reduce N_2O emissions. Urease and nitrification inhibitors are particularly consistent in this regard. Products and placements that influence the solubilization of the fertilizer product are influenced by the pattern of precipitation and as a result produce more variable results. Similarly timing of fertilizer N application interacts with the pattern of precipitation in determining the magnitude of reduction in N_2O emissions. Determining the right rate of N fertilizer still remains one of the greatest challenges establishing a 4R program. The need to consider all N sources and non-linear nature of N_2O emissions to soil N availability complicate the determination of the right rate. The emergence tools to provide site specific measures soil N supply and plant N response would greatly assist the determinate of right rate.

There is a greater realization and understanding emerging as to the role of other soil management and cropping practices in determining the potential for N_2O emissions. The choice of the most appropriate 4R practices should consider the impact of these factors in determining the magnitude and timing of the potential for N_2O losses.

While this review has primarily focused on the potential for N_2O emissions, the potential for pollution swapping must also be considered. Practices that decrease N_2O emissions but result in increased NH_3 or NO_3^- loss do not result in increased N use efficiency. While the indirect emissions from these compounds may not be as great as direct emissions of N_2O, the overall impact on the ecosystem should be considered.

References

Abalos, D., Jeffery, S., Drury, C. F., and Wagner-Riddle, C. (2016a). Improving fertilizer management in the US and Canada for N2O mitigation: Understanding potential positive and negative side-effects on corn yields. *Agriculture Ecosystems & Environment* **221**, 214-221.

Abalos, D., Smith, W. N., Grant, B. B., Drury, C. F., MacKell, S., and Wagner-Riddle, C. (2016b). Scenario analysis of fertilizer management practices for N2O mitigation from corn systems in Canada. *Science of the Total Environment* **573**, 356-365.

Aita, C., Schirmann, J., Pujol, S. B., Giacomini, S. J., Rochette, P., Angers, D. A., Chantigny, M. H., Gonzatto, R., Giacomini, D. A., and Doneda, A. (2015). Reducing nitrous oxide emissions from a maize-wheat sequence by decreasing soil nitrate concentration: effects of split application of pig slurry and dicyandiamide. *European Journal of Soil Science* **66**, 359-368.

Akiyama, H., Yan, X. Y., and Yagi, K. (2010). Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N2O and NO emissions from agricultural soils: meta-analysis. *Global Change Biology* **16**, 1837-1846.

Bouwman, A. F., Boumans, L. J. M., and Batjes, N. H. (2002). Emissions of N2O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles* **16**.

Burton, D. L., Zebarth, B. J., Gillarn, K. M., and MacLeod, J. A. (2008). Effect of split application of fertilizer nitrogen on N2O emissions from potatoes. *Canadian Journal of Soil Science* **88**, 229-239.

Chantigny, M. H., Rochette, P., Angers, D. A., Bittman, S., Buckley, K., Masse, D., Belanger, G., Eriksen-Hamel, N., and Gasser, M. O. (2010). Soil Nitrous Oxide Emissions Following Band-Incorporation of Fertilizer Nitrogen and Swine Manure. *Journal of Environmental Quality* **39**, 1545-1553.

Charles, A., Rochette, P., Whalen, J. K., Angers, D. A., Chantigny, M. H., and Bertrand, N. (2017). Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agriculture, Ecosystems & Environment* **236**, 88-98.

Congreves, K. A., Brown, S. E., Nemeth, D. D., Dunfield, K. E., and Wagner-Riddle, C. (2017). Differences in field-scale N2O flux linked to crop residue removal under two tillage systems in cold climates. *Global Change Biology Bioenergy* **9**, 666-680.

Congreves, K. A., Dutta, B., Grant, B. B., Smith, W. N., Desjardins, R. L., and Wagner-Riddle, C. (2016). How does climate variability influence nitrogen loss in temperate agroecosystems under contrasting management systems? *Agriculture Ecosystems & Environment* **227**, 33-41.

Decock, C. (2014). Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern US: Potential and Data Gaps. *Environmental Science & Technology* **48**, 4247-4256.

Dick, M. (2017). C Nitrogen stabilizers to enhance nitrogen use efficiency and reduce greenhouse gas emissions in Alberta cereal crops. Report to Fertilizer Canada.

Drury, C. F., Reynolds, W. D., Tan, C. S., Welacky, T. W., Calder, W., and McLaughlin, N. B. (2006). Emissions of nitrous oxide and carbon dioxide: influence of tillage type and nitrogen placement depth. *Soil Science Society of America Journal* **70**, 570-581.

Drury, C. F., Reynolds, W. D., Yang, X. M., McLaughlin, N. B., Welacky, T. W., Calder, W., and Grant, C. A. (2012). Nitrogen Source, Application Time, and Tillage Effects on Soil Nitrous Oxide Emissions and Corn Grain Yields. *Soil Science Society of America Journal* **76**, 1268-1279.

Drury, C. F., Yang, X. M., Reynolds, W. D., Calder, W., Oloya, T. O., and Woodley, A. L. (2017). Combining Urease and Nitrification Inhibitors with Incorporation Reduces Ammonia and Nitrous Oxide Emissions and Increases Corn Yields. *Journal of Environmental Quality* **46**, 939-949.

Drury, C. (2017). Can the Combined Effects of Nitrogen Fertilizer Placement and Enhanced Efficiency Fertilizers Reduce N Losses from Grain Corn Production in Ontario

Eagle, A. J., Olander, L. P., Locklier, K. L., Heffernan, J. B., and Bernhardt, E. S. (2017). Fertilizer Management and Environmental Factors Drive N2O and NO3 Losses in Corn: A Meta-Analysis. *Soil Science Society of America Journal* **81**, 1191-1202.

Engel, R., Liang, D. L., Wallander, R., and Bembenek, A. (2010). Influence of Urea Fertilizer Placement on Nitrous Oxide Production from a Silt Loam Soil. *Journal of Environmental Quality* **39**, 115-125.

Fernandez, F. G., Venterea, R. T., and Fabrizzi, K. P. (2016). Corn Nitrogen Management Influences Nitrous Oxide Emissions in Drained and Undrained Soils. *Journal of Environmental Quality* **45**, 1847-1855.

Fertilizer Institute Scientific Advisory Group (FISAG) (2015) Science discussion document (SDD). Fieldprint Calculator N2O revision for GHG metric. Fertilizer Institute. February, 2015.

Fujinuma, R., Venterea, R. T., and Rosen, C. (2011). Broadcast Urea Reduces N2O but Increases NO Emissions Compared with Conventional and Shallow-Applied Anhydrous Ammonia in a Coarse-Textured Soil. *Journal of Environmental Quality* **40**, 1806-1815.

Gao, X. P., Asgedom, H., Tenuta, M., and Flaten, D. N. (2015). Enhanced Efficiency Urea Sources and Placement Effects on Nitrous Oxide Emissions. *Agronomy Journal* **107**, 265-277.

Gao, X. P., Parsonage, S., Tenuta, M., Baron, K., Hanis-Gervais, K., Nelson, A., Tomasiewicz, D., and Mohr, R. (2017). Nitrogen Fertilizer Management Practices to Reduce N2O Emissions from Irrigated Processing Potato in Manitoba. *American Journal of Potato Research* **94**, 390-402.

Giweta, M., Dyck, M. F., and Malhi, S. S. (2017). Growing season nitrous oxide emissions from a Gray Luvisol as a function of long-term fertilization history and crop rotation. *Canadian Journal of Soil Science* **97**, 474-486.

Han, Z., Walter, M. T., and Drinkwater, L. E. (2017). N2O emissions from grain cropping systems: a meta-analysis of the impacts of fertilizer-based and ecologically-based nutrient management strategies. *Nutrient Cycling in Agroecosystems* **107**, 335-355.

Helgason, B. L., Janzen, H. H., Chantigny, M. H., Drury, C. F., Ellert, B. H., Gregorich, E. G., Lemke, R. L., Pattey, E., Rochette, P., and Wagner-Riddle, C. (2005). Toward improved coefficients for predicting direct N2O emissions from soil in canadian agroecosystems. *Nutrient Cycling in Agroecosystems* **72**, 87-99.

Jamali, H., Quayle, W., Scheer, C., and Baldock, J. (2016). Mitigation of N2O emissions from surface-irrigated cropping systems using water management and the nitrification inhibitor DMPP. *Soil Research* **54**, 481-493.

Jin, V. L., Baker, J. M., Johnson, J. M. F., Karlen, D. L., Lehman, R. M., Osborne, S. L., Sauer, T. J., Stott, D. E., Varvel, G. E., Venterea, R. T., Schmer, M. R., and Wienhold, B. J. (2014). Soil Greenhouse Gas Emissions in Response to Corn Stover Removal and Tillage Management Across the US Corn Belt. *Bioenergy Research* **7**, 517-527.

Kariyapperuma, K. A., Wagner-Riddle, C., Furon, A. C., and Li, C. S. (2011). Assessing Spring Thaw Nitrous Oxide Fluxes Simulated by the DNDC Model for Agricultural Soils. *Soil Science Society of America Journal* **75**, 678-690.

Kryzanowski, L. (2018) Nitrogen Fertilizer Management to Mitigate N_2O Emissions in Alberta. PowerPoint Presentation provided by Len Kryzanowski. Jan 17, 2018.

Kryzanowski, L. Wallace, T., Montgomery, G., Sprout, C., Lohstraeter, G., Powers, L., Wagner-Riddle, C. (2018) Manure Management to Reduce Greenhouse Gas and Ammonia Emissions. PowerPoint Presentation provided by Len Kryzanowski. Jan 17, 2018.

Li, C. L., Hao, X. Y., Blackshaw, R. E., Clayton, G. W., O'Donovan, J. T., and Harker, K. N. (2016). Nitrous Oxide Emissions in Response to ESN and Urea Application in a No-Till Barley Cropping System. *Communications in Soil Science and Plant Analysis* **47**, 692-705.

Linn, D. M., and Doran, J. W. (1984). EFFECT OF WATER-FILLED PORE-SPACE ON CARBON-DIOXIDE AND NITROUS-OXIDE PRODUCTION IN TILLED AND NONTILLED SOILS. *Soil Science Society of America Journal* **48**, 1267-1272.

Maharjan, B., and Venterea, R. T. (2013). Nitrite intensity explains N management effects on N2O emissions in maize. *Soil Biology & Biochemistry* **66**, 229-238.

Malhi, S. S., Grant, C. A., Johnston, A. M., and Gill, K. S. (2001). Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. *Soil & Tillage Research* **60**, 101-122.

Malhi, S. S., and Nyborg, M. (1984). INHIBITING NITRIFICATION AND INCREASING YIELD OF BARLEY BY BAND PLACEMENT OF THIOUREA WITH FALL-APPLIED UREA. *Plant and Soil* **77**, 193-206.

Nikiema, P., Akinremi, O. O., and Tenuta, M. (2016). Nitrous oxide emissions as affected by liquid and solid pig manures applied to annual and perennial forage crops on a sandy loam soil. *Canadian Journal of Soil Science* **96**, 361-371.

Omonode, R. A., Halvorson, A. D., Gagnon, B., and Vyn, T. J. (2017). Achieving Lower Nitrogen Balance and Higher Nitrogen Recovery Efficiency Reduces Nitrous Oxide Emissions in North America's Maize Cropping Systems. *Frontiers in Plant Science* **8**.

Pelster, D. E., Chantigny, M. H., Rochette, P., Angers, D. A., Laganiere, J., Zebarth, B., and Goyer, C. (2013). Crop residue incorporation alters soil nitrous oxide emissions during freeze-thaw cycles. *Canadian Journal of Soil Science* **93**, 415-425.

Risk, N., Snider, D., and Wagner-Riddle, C. (2013). Mechanisms leading to enhanced soil nitrous oxide fluxes induced by freeze-thaw cycles. *Canadian Journal of Soil Science* **93**, 401-414.

Robertson, G. P., and Vitousek, P. M. (2009). Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. *Annual Review of Environment and Resources* **34**, 97-125.

Rochette, P., Angers, D. A., Belanger, G., Chantigny, M. H., Prevost, D., and Levesque, G. (2004). Emissions of N2O from alfalfa and soybean crops in eastern Canada. *Soil Science Society of America Journal* **68**, 493-506.

Rochette, P., and Janzen, H. H. (2005). Towards a revised coefficient for estimating N2O emissions from legumes. *Nutrient Cycling in Agroecosystems* **73**, 171-179.

Rochette, P., Liang, C., Pelster, D., Bergeron, O., Lemke, R., Kroebel, R., MacDonald, D., Yan, W., and Flemming, C. (2018). Soil nitrous oxide emissions from agricultural soils in Canada: Exploring relationships with soil, crop and climatic variables. *Agriculture, Ecosystems & Environment* **254**, 69-81.

Rochette, P., Worth, D. E., Huffman, E. C., Brierley, J. A., McConkey, B. G., Yang, J. Y., Hutchinson, J. J., Desjardins, R. L., Lemke, R., and Gameda, S. (2008a). Estimation of N2O emissions from agricultural soils in Canada. II. 1990-2005 inventory. *Canadian Journal of Soil Science* **88**, 655-669.

Rochette, P., Worth, D. E., Lemke, R. L., McConkey, B. G., Pennock, D. J., Wagner-Riddle, C., and Desjardins, R. L. (2008b). Estimation of N2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. *Canadian Journal of Soil Science* **88**, 641-654.

Rose, T. J., Wood, R. H., Rose, M. T., and Van Zwieten, L. (2018). A re-evaluation of the agronomic effectiveness of the nitrification inhibitors DCD and DMPP and the urease inhibitor NBPT. *Agriculture Ecosystems & Environment* **252**, 69-73.

Smith, W. N., Grant, B. B., Desjardins, R. L., Worth, D., Li, C., Boles, S. H., and Huffman, E. C. (2010). A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada. *Agriculture Ecosystems & Environment* **136**, 301-309.

Snyder, C. S. (2017). Enhanced nitrogen fertiliser technologies support the '4R' concept to optimise crop production and minimise environmental losses. *Soil Research* **55**, 463-472.

Snyder, C. S., Davidson, E. A., Smith, P., and Venterea, R. T. (2014). Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions. *Current Opinion in Environmental Sustainability* **9-10**, 46-54.

Statistics Canada (2018). Fertilizer Shipments Survey. http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&lang=en&db=imdb&adm=8&dis=2&SDDS=5148. Accessed January 3, 2018.

Tenuta, M., Gao, X. P., Flaten, D. N., and Amiro, B. D. (2016). Lower Nitrous Oxide Emissions from Anhydrous Ammonia Application Prior to Soil Freezing in Late Fall Than Spring Pre-Plant Application. *Journal of Environmental Quality* **45**, 1133-1143.

Tenuta, M. (2017). Limiting loss of fall applied N fertilizer in the humid condition of Manitoba using enhanced efficiency fertilizer. Report to Fertilizer Canada.

Thapa, R., Chatterjee, A., Awale, R., McGranahan, D. A., and Daigh, A. (2016). Effect of Enhanced Efficiency Fertilizers on Nitrous Oxide Emissions and Crop Yields: A Meta-analysis. *Soil Science Society of America Journal* **80**, 1121-1134.

Thomas, B. W., Hao, X. Y., Larney, F. J., Goyer, C., Chantigny, M. H., and Charles, A. (2017). Non-Legume Cover Crops Can Increase Non-Growing Season Nitrous Oxide Emissions. *Soil Science Society of America Journal* **81**, 189-199.

Uzoma, K. C., Smith, W., Grant, B., Desjardins, R. L., Gao, X. P., Hanis, K., Tenuta, M., Goglio, P., and Li, C. S. (2015). Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model. *Agriculture Ecosystems & Environment* **206**, 71-83.

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M. A., Linquist, B., and van Groenigen, K. J. (2013). Climate, duration, and N placement determine N2O emissions in reduced tillage systems: a meta-analysis. *Global Change Biology* **19**, 33-44.

Venterea, R. T., and Coulter, J. A. (2015). Split Application of Urea Does Not Decrease and May Increase Nitrous Oxide Emissions in Rainfed Corn. *Agronomy Journal* **107**, 337-348.

Venterea, R. T., Dolan, M. S., and Ochsner, T. E. (2010). Urea Decreases Nitrous Oxide Emissions Compared with Anhydrous Ammonia in a Minnesota Corn Cropping System. *Soil Science Society of America Journal* **74**, 407-418.

Vyn, T. J., Halvorson, A. D., and Omonode, R. A. (2016). "Relationships of Nitrous Oxide Emissions to Fertilizer Nitrogen Recovery Efficiencies in Rain-fed and Irrigated Corn Production Systems: Data Review."

Wagner-Riddle, C. (2017). Can application of enhanced efficiency fertilizers at planting reduce N losses from grain corn production? Report to Fertilizer Canada.

Zebarth, B. J., Snowdon, E., Burton, D. L., Goyer, C., and Dowbenko, R. (2012). Controlled release fertilizer product effects on potato crop response and nitrous oxide emissions under rain-fed production on a medium-textured soil. *Canadian Journal of Soil Science* **92**, 759-769.