Economic Effectiveness of Protocols for Agricultural Nitrous Oxide Emissions Reduction (NERP)

AGRI-FOOD
ECONOMIC SYSTEMS

Al Mussell, Anatoliy Oginskyy, Dan Heaney,
Claudia Wagner-Riddle, and Diego Abalos Rodriguez

May, 2015

EXECUTIVE SUMMARY

The purpose of this study was to develop a framework to determine the economic effectiveness of adopting Nitrous oxide Emission Reduction Protocol (NERP) beneficial management practices (BMP's) with for major crops and geographical regions in Canada. Consistent with this, the literature was surveyed to understand the effects of alternate nitrogen fertility practices and the resulting effects on nitrous oxide emissions. Based upon this literature, NERP-consistent scenarios were developed for nitrogen management in major crops in Alberta (canola, wheat, and barley) and Ontario (corn and winter wheat), along with a baseline reference scenario for these crops. The effects of these were simulated using input and output prices and a nitrous oxide emission model to provide agronomic, economic, and nitrous oxide emissions results.

The results showed the following:

- The costs per acre of overall fertility management are lowest under the baseline scenario and the highest for the Advanced NERP, followed by the Basic NERP
- The profit margin over fertility cost was generally the highest for the Advanced NERP, followed by the Basic NERP, followed by the baseline. The exceptions were corn in which the Basic scenario had lower returns compared with the baseline, and winter wheat in which an Advanced scenario was not developed
- The economic benefit of the NERP scenarios was material. For example, the differential returns from Advanced versus baseline scenarios ranged from $29/acre to $71/acre. This conclusion was not affected by observed changes in crop and fertilizer prices.
- The nitrous oxide emission reduction effects observed were material. On a per acre basis, the Advanced scenario reduced emissions by about 29% versus baseline for western Canada, and the advanced scenario for Ontario corn reduced nitrous oxide emissions by about 33% versus baseline
- NERP scenarios that were both economically feasible and efficacious in reducing nitrous oxides for Ontario winter wheat were difficult to isolate. The basic scenario for winter wheat had larger nitrous oxide emissions with the baseline on a per acre basis, and comparable emissions on a per bushel basis.

These results suggest that while NERP practices are likely to increase per acre fertility costs, the benefits of adopting these practices exceed the additional costs- in both economic and nitrous oxide emission terms.

Contents

EXECUTIVE SUMMARY 2

1 Introduction 4

1.1 Purpose and Objectives 4

1.2 Organization of the Report 5

2 Environmental Benefits of Intensification and Nitrous Oxide BMP's 6

2.1 Sustainability and Intensification in Land Use 6

2.2 Nitrogen Beneficial Management Practices- Source, Rate, Timing, Placement 7

2.2.1 Nitrogen Sources 7

2.2.2 Nitrogen Application Rates 13

2.2.3 Application Timing and Placement 14

2.3 Observations 18

3 Model Development 19

3.1 Model Scope 19

3.2 Model Structure 23

3.3 Data 28

4 Results 30

4.1 Agronomic Results 30

4.2 Economic Results 30

4.3 Nitrous Oxide Emission Results 35

4.4 Sensitivity Analysis 37

4.5 Interpretation 37

5 Conclusions 40

1 Introduction

Intensification in agriculture, with its associated economic benefits, is closely related to intensification in land and water use and the development of land/water-saving technologies. Increased yields mean that less land and water must be consumed to produce a given level of output, requiring less labour input. In addition, increased yields mean that less land must be converted unto agricultural use to supply a given level of output.

Yields of crops have increased in Canada and throughout the developed world. The extent of increase in agricultural productivity improvement needs to be appreciated. For example, Ontario corn yields literally doubled between 1970 and 2012, from barely 80 bushels/acre to about 160 bushels/acre. A similar pattern exists in western Canada; Alberta wheat yields have increased by more than 50% since the mid-1970's from around 30 bushels per acre to almost 50 bushels/acre recently. In order to produce the same volume of corn and wheat as occurs today absent these yield improvements would require a markedly larger agricultural land base.

This trend is true more broadly. Ausubel *et al* document dramatic increases in crop yields and land "saved" from conversion to agricultural use from North America, Europe, Asia. Robert Thompson (2010) has noted that "A century ago, cereal grain yields in Western Europe and the United States were little higher than those observed in sub-Saharan Africa today. The large increases in productivity since then have reduced the unit cost of production and kept the price of food lower, benefitting farmers through higher household incomes and low-income consumers who spend the largest fraction of their incomes on food. Moreover, this has made famine a rarity in the world and has allowed millions of hectares of trees to remain standing in the world's forests instead of being cut to make way for an expanded area under cultivation."

An important aspect of crop yield increases has been improvement in soil fertility and increased rates of fertilizer and nutrient application. At the same time, the application of nutrients, especially nitrogen, has received increased attention as a source of greenhouse gases. In particular, nitrous oxides have a very high global warming potential compared with other greenhouse gases, and nitrogen fertilizers are sources of nitrous oxide emissions.

1.1 Purpose and Objectives

The purpose of this study is is to develop a framework to determine the economic effect of adopting NERP BMP's with respect to major crops and geographical regions. The objectives of the study are:

- To understand the existing knowledge base regarding GHG's and specific fertility practices
- To describe an economic baseline scenario for a range of cropping systems- western and eastern Canada

- To develop appropriate scenarios to which NERP protocols could be applied
- To measure the economic and effects on nitrous oxide emisions of different NERP protocols

1.2 Organization of the Report

Section 2 below provides a review of the context for intensive land management and a review literature review on approaches and scenarios relevant to NERP evaluation. Section 3 provides an overview of the baseline model. Section 4 presents the agronomic, economic, and emissions results. Section 5 concludes the report

2 Environmental Benefits of Intensification and Nitrous Oxide BMP's

This section helps establish the context for nitrogen use in fertility and the development of beneficial management practices (BMP's) for nitrous oxides.

2.1 Sustainability and Intensification in Land Use

Intensification creates environmental benefits. This may initially seem counterintuitive. However, agrarian landscapes are not "natural"; farmland in use today was historically converted from some prior, pristine state into agricultural use. Intensification of existing agricultural land use reduces the extent to which new land must be converted into agricultural use to increase production; this effect is critical in reducing carbon and water footprint, and in protecting other uses such as wildlife habitat.

For example, Burney *et al* (2010) found that agricultural intensification between 1961 and 2005 avoided the release of about 161 gigatons of carbon. They observed that "Our results demonstrate the importance of land use change emissions over direct emissions of methane and nitrous oxide from agricultural systems, and suggest that the climatic impacts of historical agricultural intensification were preferable to those of a system with lower inputs that instead expanded cropland to meet global demand for food" (Burney et al, 2010). Recent work by Stephenson *et al* (2013) found that genetic improvements in major field crops between 1965 and 2004 saved between 18 and 27 million hectares of land conversion into agricultural use.

With regard to biodiversity effects, most of the evidence comes from developing countries where new land is currently being converted to agricultural use. Phalan *et al* (2011) compared the densities of tree and bird species according to varying levels of agricultural intensity in India and Ghana. They found that more species were negatively impacted by agriculture than benefitted from it, indicating a benefit to intensifying the land base and leaving other lands undisturbed. Similar effects were observed by Guitierrez-Velez *et al* (2011) in oil palm production in Peru, and across a range of crops in tropical countries by Phalan *et al* (2013).

The environmental effects of intensification are also complex. Increased yields per acre initially increase profitability, but can also have a secondary effect of decreasing prices; this has been hypothesized to result in decreasing agricultural land use from previous levels. However, this has generally not occurred. For example, Rudel *et al* (2009) used global data from 1970 to 2005 and national data from 1990 to 2005 for 10 crops to determine whether intensification had reduced the agricultural land base. For the most part land "sparing" due to increases in yields was not observed; however, the authors noted a number of other contextual changes that help explain this- such as increased trade, growth in livestock demand, political shifts, etc. In noting that empirical studies indicate that biodiversity protection is more effective under land sparing over land "sharing" (managing land less intensively to provide both agricultural production and biodiversity) Ramankutty and Rhemtulla (2012) point out that it is unclear that land sparing has actually reduced acreage under agricultural use, because a reliable baseline has not been established. Baker *et al* (2013) found that, based on observed yield growth from 1960-2009, increased crop productivity in the United States was land-saving and thus directly greenhouse gas emission reducing, but note that the downstream relationships are complex. Increased feed grain yields decrease feed grain prices, resulting in increased livestock production with its associated greenhouse gas output, which in turn reduces feed grains available for export, increasing land conversion into agriculture in feed grain importing countries.

Intensification has mitigated the extent to which more land and water are used in agriculture as food production has increased. This has created very significant environmental benefits, particularly in terms of greenhouse gas emissions, and biodiversity. Absent the agricultural intensification of recent decades, there would be less area of natural ecosystem to support wildlife habitat, less water available for other uses, and more greenhouse gas emissions.

As land use intensifies and relatively more nutrients, water, and crop care products are used to minimize the footprint of agriculture, there are risks associated with greater intensification. While these risks are a positive tradeoff in comparison to extending agricultural use into pristine lands, mitigation effort is warranted. Beneficial management practices for nitrous oxides represent a means of reducing emissions risks and the prospect for adverse effects from land use intensification.

2.2 Nitrogen Beneficial Management Practices- Source, Rate, Timing, Placement

Beneficial management practices identify synergies that can be obtained through integration of nitrogen management and related practices. Quantitatively estimating these effects is challenging. The literature reports on numerous experiments in which a subset of one or two factors are manipulated while holding the others constant. This is necessary as performing a fully integrated experiment even for a single crop at a single site rapidly becomes unwieldy both operationally and statistically. For example, comparing three urea nitrogen sources (urea, polymer coated urea, urease inhibited urea) at four rates (check, below-recommended, recommended, above-recommended) using the three most common placements (broadcast, surface banded, subsurface banded) and alternative application timing (spring and fall) requires seventy-two treatments. Given these limitations, the synergistic effects when many factors are combined into a nutrient management system must to a large extent be inferred from multiple datasets through tools such as modeling and meta-analysis as they cannot realistically be measured directly. With these caveats acknowledged, it is important to understand the roles of nitrogen source, rate, timing, and placement in BMP’s.

2.2.1 Nitrogen Sources

Commonly used conventional nitrogen fertilizer sources used in Canada are urea, anhydrous ammonia, urea-ammonium nitrate (UAN), and ammonium sulfate (Canadian Fertilizer Institute, 2014). All of these sources when used with appropriate management practices can increase yields about equally well per unit of nitrogen applied (Johnston et al. 1997; Grant et al. 2002). Agronomists and farmers have tended to approach nitrogen source selection as though these sources were entirely equivalent or fungible. Choosing the right N source has generally been based on price; grower preferences for placement equipment; and blending, storage, safety, and handling characteristics.

However, different conventional sources may in some circumstances vary in nitrous oxide emissions. Halvorsen et al. (2014a) found that UAN produced lower emissions than urea in irrigated cropping systems in Colorado. Tenuta and Beauchamp (2003) compared sources in laboratory and field studies and found that emissions ranked urea > ammonium sulfate > ammonium nitrate. Urea has been reported to lower emissions compared to anhydrous ammonia in rain-fed corn production systems in Minnesota (Venterea et al. 2010). On the other hand, Burton et al. (2008) found no difference between urea and anhydrous ammonia in Manitoba. Decock (2014) in a recent review and meta-analysis of nitrogen management practices in mid-west corn systems, found that source differences can have a considerable impact on fertilizer induced emissions. In her analysis, conventional sources ranked emissions anhydrous ammonia > UAN > ammonium nitrate > urea when emissions were compared per unit of nitrogen applied, with emissions from urea being on average less than half of those from anhydrous ammonia.

Controlled Release Nitrogen Fertilizers

The gradual improvement of enhanced efficiency fertilizer has been the major development in nitrogen source over the past two decades. One approach to enhanced efficiency is to physically control release of nutrients out of granular products with a membrane or coating. Polymer coated urea sold by Agrium as ESN™ has been available commercially in Western Canada for a decade and is being increasingly adopted by producers. The price premium relative to uncoated urea has narrowed considerably as ESN has become a more mainstream product. ESN can be applied alone but there is a growing trend to apply it in blends with uncoated urea. One of the benefits of ESN is increased seed safety relative to uncoated urea when seed row applied (Hadelein et al. 2001; Malhi and Lemke, 2013; McKenzie et al. 2007). Another may be preventing early season nitrogen uptake by weeds (Blackshaw et al. 2011).

Stabilized Sources of Nitrogen

A second approach to enhancing efficiency is by adding chemical inhibitors to fertilizer. The principle behind these products is to slow conversion of urea to ammonium and reduce the rate of volatilization and/or limit the conversion of ammonium to nitrate through nitrification and prevent nitrate accumulation, potentially reducing denitrification and leaching. Use of these stabilized nitrogen sources reduces risk of loss, and when timed appropriately can synchronize supply with crop demand. Since nitrification and denitrification are the major processes responsible for direct nitrous oxide emissions and volatilization and leaching the processes contributing to indirect emissions slowing the conversions potentially lowers nitrous oxide contributions from fertilizer.

The most commonly used urease inhibitor is N-(n-butyl) thiophosphoric triamide (NBPT). It has been extensively field and laboratory tested in North America and elsewhere, with well over a thousand individual trials completed to date (Saggar et al. 2013). In Canada NBPT is sold under the brand names Agrotain™ as a stand-alone product or in combination with the nitrification inhibitor dicyandiamide (DCD) as Agrotain Plus™. These products can be added to granular or liquid urea containing fertilizers. Urea pre-treated with urease inhibitor and DCD is also available under the trade names SuperU™.

Nitrification Inhibitors

Treating nitrogen fertilizer with nitrification inhibitors is the third approach to creating an enhanced-efficiency fertilizer. There are three nitrification inhibitors that are commercially available in North America: nitrapyrin, dicyandiamide (DCD), and ammonium thiosulfate (ATS). Nitrapyrin is the active ingredient found in the DOW® products N-Serve® and Instinct®. Nitrapyrin was initially registered for the US market in 1974. Although tested in Canadian soils in the 1970's and 80's, it was never registered. Nitrapyrin is quite effective even at relatively low rates. Originally nitrapyrin was difficult to handle and only available for use with anhyrous ammonia (N-Serve). More recent microencapsulated formulations (Instinct and Instinct II) can be used with UAN and granular products as well as liquid manure. Dicyandiamide (DCD) is the active ingredient in nitrification inhibitors such as Agrotain Plus®, SuperU®, and Guardian®. Dicyandiamide is required at a significantly larger concentration to be effective. Ammonium thiosulfate is also used as a sulfur source in fluid fertilizer blends.

Agronomic Results

Yield benefits from ESN appear to be variable depending on the cropping system and site-specific conditions of the experiments. Haderlein et al. (2001) in their comparison of seed-placed ESN to side-banded conventional urea at multiple rates reported no yield advantage. But seed-placed ESN did consistently increase nitrogen uptake. Grant et al. (2012), in a multiple site, multiple year study in W. Canada, found no consistent improvement in yield relative to uncoated urea when ESN was side-banded in spring. McKenzie et al (2007) measured no yield differences relative to uncoated urea when ESN was side-banded at time of seeding on winter wheat in S. Alberta but substantial positive differences when it was seed-placed. In later experiments, they found ESN banded at seeding increased yield slightly but was comparable to other forms when spring broadcast (McKenzie et al. 2010). Beres et al. (2010) also working with winter wheat in Southern and Central Alberta, reported ESN side-banded at seeding consistently outperformed conventional urea broadcast in spring. Working in Northern Alberta and Saskatchewan over a four year rotation, Malhi et al. (2010) reported enhanced yield and nitrogen recovery in crops receiving ESN in wetter than normal years. Blackshaw et al. (2011) found canola yield with ESN was similar to urea in 14 of 20 site-years and increased canola yield in 4 site-years. In a Minnesota study, ESN blends showed positive protein and yield benefits in spring wheat production under warm moist spring conditions while yield decreased and protein increased under cool dry spring conditions (Farmaha and Sims 2013).

Khakbazan et al. (2013) estimated net revenue differences among treatments using the data from Grant and colleagues and found that overall ESN provided no economic benefit. Interestingly when spring banded at the recommended, ESN provided equal (19) or better (1) net revenue relative to urea in 20 of the 24 site-years where a statistical comparison was provided. This suggests there may be situations where realizing the environmental benefits of ESN may be at least revenue neutral for the producer.

In Western Canadian soils, NBPT has been shown to prevent losses through ammonia volatilization when urea is surface applied (Rawluk et al. 2001). This has not consistently resulted in agronomic benefit. Experiments on the use of NBPT to improve seed-row safety in Western Canada have met with mixed results. Research showing improved seedling emergence with NBPT treated urea on wheat, barley, or canola has been reported by Xiaobin et al. (1995); Grant and Bailey (1999); Malhi et al. (2003); and Karamanos et al., (2004). More recently, Malhi and Lemke (2013) found no benefit on seedling emergence in a three-year study on canola and wheat. Grant (2014) found NBPT was not effective in increasing grain yield of spring wheat when applied with urea but did have some positive effects when used with UAN in broadcast (spray) applications. McKenzie et al. 2010 measured small yield increases with NBPT treated urea relative to ESN when broadcast in early spring on winter wheat but no difference relative to urea. He concluded that the negligible improvements were likely due to the low risk of nitrogen loss in the study area. Field trials run for winter wheat in Ontario have not found a yield response to date (Johnson, 2013 and Johnson, 2015).

A meta-analysis by Abalos et al. (2014) showed that nitrification inhibitors and urease inhibitors can be recommended in order to increase both crop yields and nitrogen use efficiency (mean increase of 7.5% and 12.9%, respectively). However, the effectiveness of these products was dependent on the environmental and management factors of the studies evaluated. Larger yield increases were found in coarse-textured soils, irrigated systems and/or crops receiving high N fertilizer rates (i.e. above crop N requirements). In alkaline soils ($\text{pH} \geq 8$), the urease inhibitor NBPT produced the largest yield increase. These authors concluded that given that their use represents an additional cost for farmers, understanding the best management practices to maximize their effectiveness is paramount to allow effective comparison with other practices that increase crop productivity and nitrogen use efficiency.

Table 2.1 Mean effect on N_2O emissions and yield of EENFs.

EENFs	General effect	
	N_2O Mitigation (%)	Yield Increase (%)
Nitrification inhibitors	38*	4.6***
Urease inhibitors	-	10***
Nitrification + Urease	38**	8.8***
Slow release fertilizers	35*	-

* Akiyama et al. (2010)
** Decock (2014)
*** Abalos et al. (2014)
\- Unknown

Nitrous Oxide Emission Effects

Akiyama et al. (2010) performed a meta-analysis on the effectiveness of enhanced-efficiency fertilizers as mitigation options for nitrous oxide emissions using 113 datasets from 35 studies. They found nitrification inhibitors and polymer coated urea reduced nitrous oxide emissions 38% and 35% respectively. Reductions varied with cropping system and soil type. The results were more equivocal for urease inhibitors, which over all showed little or no effectiveness in reducing nitrous oxide emissions in the study. Three of the six data sets analyzed for NBPT were from a site at Brandon, Manitoba where nitrous oxide emissions from treated urea, untreated urea and the zero nitrogen control were similar in two out of three years (Burton et al 2008).

A recent summary of experiments on irrigated corn systems in Colorado performed over multiple sites and multiple years found that controlled release and stabilized nitrogen sources consistently reduced direct nitrous oxide emissions during the growing season relative to untreated urea and UAN (Halvorson et al. 2014a). The controlled release source ESN, reduced nitrous oxide emissions by 42% compared with urea and 14% compared with UAN in no-till and strip-till systems but had no effect in a conventional tillage system. Granular urea treated with both a urease and a nitrification inhibitor (SuperU) emitted 46% less nitrous oxide than urea and 21% less than UAN. A UAN source similarly stabilized with urease and nitrification inhibitors (UAN+Agrotain Plus) reduced nitrous oxide emissions by 61% compared with granular urea and 41% compared with UAN alone. Interestingly, UAN reduced nitrous oxide emissions by 35% compared with urea in their studies.

In an Alberta study focused on canola production systems, nitrous oxide emissions across three sites and three years were reduced by an average of 20% for spring side-banded ESN compared to conventional urea on canola (Li et al 2012). Soon et al. (2011), in a study in Dark Gray soils, compared emissions from fall and spring banded urea and ESN at two sites over three years. They concluded that ESN can increase available N during the growth period and reduce nitrous oxide loss in some years compared with urea. Other studies from cool dry regions in the interior plains generally show a reduction of direct emissions with enhanced efficiency sources in a range of soil types and cropping systems (Burton et al. 2008; Hyatt et al. 2010; Venterra et al. 2011). In more humid climates, enhanced efficiency sources may have little or no positive benefits on direct emissions and may actually increase emissions depending on the timing and intensity of rainfall events (Sistani et al. 2011; Parkin et al. 2014).

In irrigated corn studies in Colorado, reduced N_2O emissions have been reported from fertilizers with NIs and polymer-coated urea (Halvorson et al., 2010, 2012; Halvorson and Del Grosso, 2012). For example, polymer-coated urea (ESN), reduced N_2O emissions by 42% compared with urea and 14% compared with UAN solution in no-till and strip-till environments, but had no effect in a conventional tillage environment. Super U reduced N_2O emissions by 46% compared with urea and 21% compared with UAN. AgrotainPlus reduced N_2O emissions by 61% compared with urea and 41% compared with UAN alone. A slow-release UAN source (UAN + Nfusion) reduced N_2O emissions by 57% compared with urea and 28% compared with UAN. In Kentucky (2009-2010), Sistani et al. (2011) measured N_2O emissions from rain-fed corn fertilized with ESN, Super U, conventional urea, UAN, and AgrotainPlus. In 1 yr of their 2-yr study, these investigators found that cumulative N_2O emissions were generally not significantly different among fertilizer types, and in the other year, the enhanced efficiency fertilizer, ESN, supported higher N_2O emissions.

In Minnesota (2008-2010), effects of conventional granular urea, ESN and Super U were evaluated during a rain-fed corn crop (Venterea et al. 2011). Neither of two EENFs decreased N_2O emissions compared with urea, but they reduced soil NO_3^-. Therefore, both products could have water quality and greenhouse gas benefits because leached NO_3^- can be converted to N_2O. In Iowa (2009-2011), Parkin and Hatfield (2013) observed no reductions in cumulative seasonal N_2O emissions from treatments fertilized with the EENFs (ESN, Super U, AgrotainPlus) in any of the study years. Generally, N_2O emissions were significantly higher than emissions from the check (no fertilizer) treatment. There were no differences among fertilizer types except in 2009 when the ESN treatment had significantly higher emissions than the check, UAN, and AgrotainPlus treatments. These authors stated that, due to the episodic nature of N_2O emissions induced by rainfall events, reduction of N_2O emissions through the use of EENFs may be limited in rainfed regions.

In Ontario (2004-2006), a study was conducted to determine the effect of N fertilizer source (regular urea vs. coated urea) on N_2O emissions and corn grain yields from soil under conventional tillage (CT), zone tillage (ZT), or no-tillage (NT) (Drury et al. 2012). Polymer-coated urea was most effective in 2004 under CT when the soil moisture was high in the first month after planting due to antecedent soil moisture conditions and rainfall. Under these wetter conditions, N_2O emissions were reduced by either delaying urea hydrolysis with polymer-coated urea or by using ZT instead of CT.

Experimental work in cool dry areas shows that the positive effects of enhanced efficiency fertilizers are site specific. The use of these sources does not consistently result in yield increases and in some cases can result in lower yields relative to conventional sources. They typically increase fertilizer use efficiency and reduce nitrous oxide emissions. Overall the enhanced efficiency sources have a modest potential of improving yield and return on fertilizer costs and a substantial potential for reducing nitrous oxide emissions. The challenge is to identify the circumstances where enhanced efficiency fertilizer will have a high likelihood of providing both economic and environmental benefits. If that can be accomplished they will be an important technology for managing nitrous oxide emissions under intensified productions regimes.

2.2.2 Nitrogen Application Rates

Nitrogen fertilizer is a major yield driver for non-leguminous field crops (Karamanos et al. 2010). Fertilizer costs are typically the largest single variable expense for cereal and oilseed producers with the majority of fertilizer expenses on nitrogen (MAFRI 2014). Growers of grains (wheat, barley, corn) are generally sensitive to nitrogen costs and are becoming increasingly aware that fertilizing for the economic optimum involves lower rates than those required to achieve maximum yield. Moreover, there is a relationship among the nitrogen fertilizer application rate, yield, and nitrous oxide emissions. At the same time, cropping systems that are inadequately supplied with other nutrients will not make efficient use of nitrogen resulting in higher emissions, lower yields and greater quantities of residual nitrate (Snyder et al. 2009, Johnson et al. 1997).

Economic optimization of fertilizer rates requires consideration of expected growing conditions, crop prices, and fertilizer costs. Of these only fertilizer cost is usually known with certainty at the time of making the rate decision. Crop yield response to nitrogen fertilizer typically follows a pattern of near linear response giving way to a diminishing return and finally a plateau as rates increase. Since the return on nitrogen fertilizer is maximized at the rate where marginal revenue from the extra crop produced and marginal cost of the nitrogen are equal, under or over fertilizing in any given year results in reduced profit suboptimal economic performance. Finding the economic optimum nutrient rate (EONR) is difficult with so many unknowns, but by definition the EONR is less than the rate required to achieve maximum yield or agronomic optimum nutrient rate (AONR) (IPNI 2012).

In past studies, there has almost invariably been a yield response to added nitrogen observed. The few exceptions involved experiments where environmental conditions, such as lack of moisture, placed limitations on crop growth. Several authors have theorized that the rise in nitrous oxide emissions in response to fertilizer rates is relatively moderate until the nitrogen uptake capacity of the cropping system is exceeded (Bouwman et al. 2002, Grant et al. 2006, and Snyder et al. 2007). In a meta-analysis, Kim et al. (2013) examined 26 published datasets where at least four different levels of N input had been applied. They found the relationship of direct nitrous oxide emission to N input was nonlinear (exponential or hyperbolic) in 18 datasets while the relationship was linear in four datasets. They proposed based on their analysis a general sigmoidal model with a lag or low rate of increase phase, an exponential phase, and a plateau or steady state phase with the cross over point from low to exponential increase occurring at the optimal N uptake by vegetation.

The field studies that supported this model were largely from temperate cropping systems. For example, Hoben et al. (2011) working with corn in Michigan reported that nitrous oxide emissions increased substantially once the optimal rate was exceeded. Working with corn in Ontario, Ma et al. (2010) found that rates over 90 kg N/ha substantially increased nitrous oxide emissions but not yield. In a Manitoba potato study, Gao et al. (2013) found that emissions were linear overall but in their study, optimum yield as measured by marketable tubers was reached at the lowest fertilizer nitrogen rate.

While there is a large degree of variability among sites and years in the reported experimental data, the trend appears to be that direct N2O emission factors increase markedly at N input rates above plant uptake capacity. This would suggest that while nitrous oxide emissions per acre may go up with increasing nitrogen rates, the emissions intensity (kg N_2O/kg crop) is not likely to increase substantially as long as rate are kept below the agronomic optimum. If an aspect of sustainable production is to find the balance among economic and environmental goals then economic optimization of nitrogen rates will result in maximum return to the producer on their nitrogen expenditures and reduction in nitrous oxide emissions relative to the over fertilization inherent in a maximum yield approach.

Technologies available for optimizing nitrogen rates for growing conditions include optimization programs such as AFFIRM[1] which take in account fertilizer and crop prices and provide an estimate of the economic optimum rate under different moisture probabilities. The NMAN program in Ontario simulates and solves for nitrogen fertilizer application rates. These programs generally depend on soil test nitrogen as an input variable. Soil test nitrogen is considered one of the important variables for determining right rates for nitrogen on a field specific basis. In a 2012 survey of production practices in Western Canada, canola growers that soil tested reported on average a 2 bu/acre advantage over those that didn't (Smith 2013). NERP prescribes soil testing as a best management practice at all levels of application of the protocol.

Variable rate fertilization is another technology that presents the prospect to optimize nitrogen rates by more closely matching nitrogen inputs to spatial differences in crop uptake requirements. Managing variable rates can help address suboptimal economic performance of nitrogen from both under- and over-application.

2.2.3 Application Timing and Placement

Nitrogen timing and placement can have significant effects on yield, nitrogen use efficiency and nitrous oxide emissions. Typically nitrogen is spring applied at or just before seeding; fall-

---

[1] Alberta Farm Fertilizer Information and Recommendation Manager, Available from Alberta Agriculture and Rural Development as a free download at www1.agric.gov.ab.ca.

application appears to be declining. Use of split-application, with some of the nitrogen applied at or before seeding and the remainder in crop, is increasing but is still a minor practice. Fall nitrogen application reduces workload during the seeding window and takes advantage of lower fall fertilizer prices. Many producers have solved the price differential by purchasing in fall and storing on-farm.

The choice of fall over spring application timing can reduce nitrogen use efficiency and yield response particularly in finer textured soils and moister regions. Placement interacts strongly with timing and site conditions in determining the relative efficiency but there is a considerable body of evidence demonstrating that in prairie cropping systems spring-applied N generally out performs fall (Harapiak 1979; Nyborg and Leitch 1979; Bole et al. 1984; Malhi et al. 1984; Ukrainetz 1984; Nyborg and Malhi 1986, 1992; Malhi et al. 2001). The ranking from most to least effective under conventional tillage can be summarized as spring banded > fall banded > spring broadcast > fall broadcast. This suggests that 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 in all regions of the province.

Common nitrogen fertilizer sources either contain nitrogen in the ammonium form or convert to ammonium following application. (The notable exception is UAN with nitrate-N accounting for 25% of its nitrogen content.) The subsequent conversion of ammonium to nitrate is temperature dependent and early fall application allows formation of more nitrate prior to the soil freezing and increases the potential for losses prior to crop uptake the following growing season (Malhi and Nyborg 1979; Malhi and McGill 1982; Malhi et al.1984; Malhi and Nyborg 1983; Monreal et al. 1986; Malhi and Nyborg 1990a,b; Nyborg et al.1990; Nyborg et al. 1997).

The risk of overwinter loss and reduced yield response varies regionally largely dependent on soil moisture and the probability of spring saturation. Research conducted largely in the wetter black, dark gray and gray soil zones in western Canada generally indicates large reductions in efficiency that can only be partly overcome by band placement, use of inhibitors and late fall timing (Malhi and Nyborg 1979; Malhi and Nyborg 1984; Monreal et al. 1986; Malhi and Nyborg 1988a,b; Yadvinder-Singh et al. 1994; Malhi et al. 2001). Results from the brown and dark brown soil zones indicate lower risk of overwinter loss, which can be largely overcome at least in most years by banding (Bole et al. 1984; Kucey 1986; Kucey and Schaalje 1986; Malhi et al. 1992b; Malhi et al. 2001).

Site-specific factors can substantially modify these regional trends. Grant et al. (2001, 2002) found in black soils in Manitoba that grain yields with fall-applied urea and UAN tended to be lower than spring-applied on a finer textured soil but similar on a coarser textured soil. In these studies, the two sites were approximately 50 kilometers apart. Efficiency of fall application can also vary markedly with landscape position in the same field. Tiessen et al. (2005, 2006) reported grain yield and apparent recovery of fertilizer N were significantly greater for spring and late fall applications at low landscape positions, when compared with early and mid-fall applications but found no difference at high landscape positions.

The potential for loss is higher when fertilizer nitrogen is fall-applied. Denitrification during the the spring thaw can account for a substantial portion of annual nitrous oxide emissions from soils subject to freeze thaw cycles (Risk et al. 2013). This makes it likely that nitrous oxide emissions are higher with fall compared to spring fertilizer timing. However, experimental results have varied. Burton et al. (2008) found that cumulative emissions from fall-applied nitrogen were marginally greater than spring applied over a three-year study in Manitoba. Soon et al. (2011) found significantly greater emissions from fall-applied plots in some site years but not others. They did, however, report large apparent losses of nitrate that may have contributed to indirect emissions.

Subsurface band placement tends to increase nitrogen use efficiency and more effectively increase yield than broadcasting nitrogen. 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). Reduction of ammonia volatilization and leaching infers reduction of indirect nitrous oxide emissions. Whether banding (fall or spring) results in lower emissions overall is still unclear. Burton et al. (2008) found little difference in direct emissions between broadcast and banded urea in two Manitoba soils. 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 nitrous oxide emissions. However, practices that reduce direct emissions but increase ammonia emissions may still be important mitigation strategies depending on the balance between the two processes. A kilogram of volatilized ammonia-N would have a global warming potential (GWP) of approximately 4.87 kg CO_2e, while a kilogram of N lost through direct emissions of nitrous oxide results in a GWP of 487 kg CO_2e.[2]

Banding after the soil has cooled below 10°C is considered a BMP for fall nitrogen application under NERP at the basic level. Use of an enhanced efficiency fertilizer with fall-banded N is a BMP at the advanced level. The inclusion of fall application timing as an appropriate BMP under NERP will need to be reconsidered once results from some of the research currently underway become available. Early indications are that switching from fall to spring application may be one of the more effective practice changes growers can make for both improving nitrogen use efficiency and reducing nitrous oxide emissions.

The other main timing consideration is whether to apply all nitrogen at or before seeding, after seeding, or use a split application approach. From an agronomic perspective there are a number of reasons to use split applications including reducing the fertilizer volume handled at seeding,

---

[2] Based on the default IPCC emission factor for re-deposited ammonia of 0.01 kg NO_2-N/kg NH_3-N and a the GWP conversion of 310 currently used in NERP.

managing risk of low moisture in dryland cropping, matching application to uptake timing, and fine-tuning of nitrogen rates with growing conditions. Holzapfel et al. (2007) reported no yield reduction in canola from split application, but yield was depressed in wheat when little precipitation was received after N application. Karamanos et al. (2005) suggested that applying N post emergent was higher risk than applying all N at the time of seeding and that adding a significant portion of nitrogen at seeding was required to reduce that risk. Split application that places a third to half the nitrogen at or before seeding, more in drier and less in wetter conditions, combined with timely in-crop application yield about equally well under normal moisture conditions and provide growers with a tool to avoid over or under application (Lafond et al. 2008, Malhi et al. 2001).

There appears to be little difference in yield between in-soil and surface banding using UAN under prairie conditions (Holzapfel et al. 2007). Grant (2014), working in no-till wheat production in Manitoba, compared surface application techniques applied immediately after seeding. She found that concentrating surface application in a band increased yield when UAN was the source but yields were comparable when broadcast urea was compared to surface banded urea. Johnson has observed little yield benefit to split applications of nitrogen in Ontario winter wheat except at higher rates (120 lbs/acre, or more) with use of fungicides, in which case yields can increase by 10% or more (2015 personal communication).

Split application using surface banding or in-soil bands both appear to be viable options agronomically but little work has been done comparing nitrous oxide emissions from the different placements. Halvorson et al. (2012) measured nitrous oxide emissions from ESN, SuperU, UAN+Agrotain Plus compared to subsurface banded ESN, surface banded UAN, and surface banded urea in irrigated strip-till and no-till corn systems in Colorado. They found that all sources and placements produced the same yield but sources varied significantly in cumulative growing season emissions. Surface banded UAN and SuperU reduced cumulative emissions by approximately half compare to surface applied urea, while UAN+Agrotain Plus reduced emissions by 67%. Interestingly surface banded ESN, while reducing emissions by 53% relative to urea, also had 38% lower emissions than subsurface banded ESN.

Split-applications have the potential to be a useful BMP for nitrous oxide emissions. They may be particularly effective in areas where growing season precipitation is more variable and applying all nitrogen at seeding represents a financial and environmental risk. In all likelihood the mechanism of nitrous oxide reduction would be a lower nitrogen application rates in years when the in-crop application was not applied or applied at a reduced rate. Split application is an allowable practice in NERP but producers may not have the equipment necessary to subsurface band in crop. Surface banding using UAN or UAN+Agrotain Plus appears to have relatively low emissions compared to broadcasting or surface banding urea and fits with the growing use of high clearance sprayers in cereal and oilseed production. The use of enhanced efficiency fertilizers in-crop can be an agronomic issue if it significantly delays conversion or release and uptake by the crop and needs to be approached with caution but does warrant more attention as a possible BMP under NERP.

2.3 Observations

A significant body of work examining the effects of beneficial management practices on nitrous oxide emissions has been completed since the original scientific review of the NERP in 2008. This new work generally supports the conceptual framework and suggested BMPs found in the NERP while at the same time pointing out areas where benefits can be increased by reconsidering practices at the different levels. The most important points and recommendations are as follows:

- Conventional nitrogen sources may not appear to vary much in agronomic performance but can differ markedly in nitrous oxide emissions.
- The efficacy of enhanced efficiency fertilizers in increasing yield and reducing nitrous oxide emissions is highly site specific and interacts strongly with time and place.
- Nitrous oxide emissions are not linear with respect to nitrogen rate but increase exponentially once sufficient nitrogen has been applied to maximize yield. Since the economically optimal rate is less than the rate required to maximize yield, a strategy of economic rate optimization will generally improve economic performance and reduce emission intensity.
- Fall-application of fertilizer is broadly agronomically inferior to spring application. Nitrous oxide emissions during spring thaw can be a considerable portion of annual emissions and work nearing completion in Alberta shows that switching from fall to spring application would significantly reduce overall emissions.
- Split nitrogen application has potential to help growers improve economic performance and mitigate emissions by avoiding over application. Presently cereal and oilseed growers require specialized equipment to subsoil band in-crop. Existing research suggests that source selection can significantly reduce emissions from surface banding.
- Researchers often found application of source, rate, time, and place BMPS reduce emissions more than the current reduction modifiers of 15% for basic and 25% for intermediate and advanced NERP. The newer research supports the view that the reduction modifiers are conservative. A reduction modifier of 30-35% is scientifically supportable for the advanced NERP with revisions to the required BMPs.
- Winter wheat in Ontario may present fewer options consistent with the NERP, as spring sub-surface application is not feasible, and urease inhibitors have yet to demonstrate yield efficacy. Split nitrogen applications of nitrogen appear to only produce yield benefits at higher rates of application.

The above the basis for scenarios to test in the economic evaluation of NERP consistent protocols described in Sections 3 and 4.

3 Model Development

In order to evaluate alternative BMP scenarios, an analytical model that relates agronomic, emission, and economic information and prescribes baseline scenarios is required. The baseline scenario is then altered to represent BMP scenarios that can then be compared empirically with the baseline scenario. This section provides an overview of the structure of this model used to generate these results under baseline and BMP scenarios.

3.1 Model Scope

The purpose of the analytical model is to evaluate N_2O emission, fertilizer costs, emission-cost ratios, and cost benefit-ratios under different nitrogen application scenarios for crop production in Western Canada (Alberta) and Eastern Canada (Ontario). The N_2O accounting scope for this research is based on the nitrogen coming from commercial fertilizers, manure, and crop residuals, as outlined in Figure 3.1 below. Emission of N_2O from other sources such as livestock production and variations in manure management are not considered.

As illustrated in Table 3.1 the representative crops assumed for Alberta are canola, spring wheat, and barley. First, average yields of the three crops for areas representative of Dark Brown, Black, and Grey/Peace soil zones in Alberta were obtained, with fertility requirements to achieve these yields solved by the AFFIRM model, assuming medium spring moisture, average growing season precipitation, and medium soil texture seeding into stubble.

- The baseline scenario was developed assuming that a 90% yield occurs reliably under the baseline fertility management based on spring surface broadcast nitrogen.
- The Basic NERP scenario is based on application of optimal rates of urea applied in bands with soil testing, and the actual index yield.
- The Advanced NERP scenario uses urease-inhibitor treated urea with soil testing and variable rate technology, and a yield level 10% over the index yield.

The crops to be assessed for Eastern Canada (Ontario) are winter wheat, and grain corn[3], as illustrated in table 3.2. Scenarios for corn and winter wheat were based on a target yield level of 150 bushels/acre for corn and 74 bushels/acre for winter wheat, and run through the NMAN software program was to estimate nitrogen fertilizer recommendations, assuming a corn-soybean-wheat rotation.

- The baseline scenario assumed that the index yield occurs for corn, and that 90% of index yield occurs for winter wheat, under fertility management based on spring surface broadcast nitrogen, with a small amount of nitrogen in starter fertilizer.
- The Basic NERP scenario is based on the timing of nitrogen application. For corn, applications were split to part surface broadcast pre-plant and part side dressed later in the spring, with a 10% reduction in nitrogen application rate, at index yield, with soil testing and variable rate technology. This is based on corn agronomy recommendations from OMAFRA Publication 811. For winter wheat, nitrogen application rates were

---

[3] It is assumed that soybeans are grown in rotation with winter wheat and corn, but nitrogen fertilizer is not applied to soybeans

Figure 3.1 Boundary of the System and N_2O Inventory

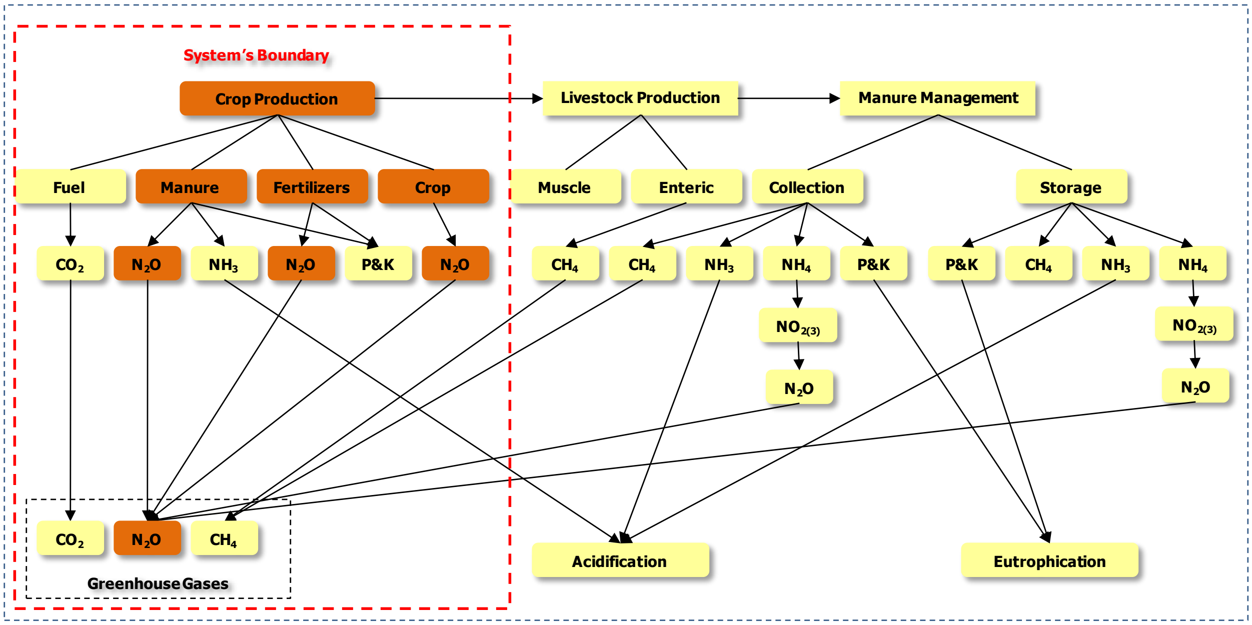


Table 3.1 NERP Scenario Design- Alberta

	Scenario		
	Baseline	**Basic NERP**	**Advanced NERP**
Fertilizer Application: Timing	Spring	Spring	Spring
Fertilizer Application: Placement	Surface Broadcast	Banded	Banded
N Source	Urea	Urea	Urea treated with urease inhibitor
N Rate	Index	Index	Index minus 5%
Soil Testing	None	Composite sampling, Two depths, Complete nutrient analysis	VRT recommendations, Sampling by management zone, two depths, complete nutrient, analysis.
Yield	Index minus 10%	Index	Index plus 10%

Table 3.2 NERP Scenario Design- Ontario

	Scenario					
	Baseline		Basic NERP		Advanced NERP	
	Corn	Winter Wheat	Corn	Winter Wheat	Corn	Winter Wheat
Fertilizer Application: Timing	Spring	Spring	Spring	Spring	Spring	N/A
Fertilizer Application: Placement	Surface Broadcast	Surface Broadcast	Split Application: Surface Broadcast, Side dress	Split Application: Surface Broadcast,	Split Application: Surface Broadcast, Side dress	N/A
N Source	UAN	UAN	UAN	UAN	UAN treated with urease inhibitor	N/A
N Rate	Index	Index	Index minus 10%	High rate	Index minus 10%	N/A
Fungicide	No	No	No	Prosaro	No	N/A
Soil Testing	None		Composite sampling, Two depths, Complete nutrient analysis	Composite sampling, Two depths, Complete nutrient analysis	VRT recommendations, Sampling by management zone, two depths, complete nutrient, analysis.	N/A
Yield	Index	Index minus 10%	Index	Index plus 10%	Index plus 10%	N/A

increased, and split application of nitrogen occurred with the use of a fungicide, resulting in a 10% yield increase over index with soil testing and variable rate technology.

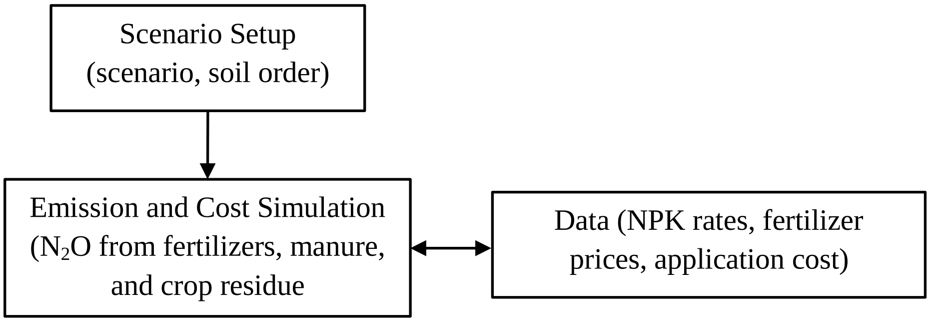
- The Advanced NERP scenario, only applied for corn, urease-inhibitor treatment in conjunction with the split nitrogen application and a yield level 10% over the index yield with soil testing and variable rate technology.

3.2 Model Structure

The economic model accepts input from the agronomic-nitrous oxide model and determines the amount and cost of fertilizer ingredients required, based on regional fertilizer price data. It also accounts for the costs of agronomic practices, such as alternative methods of application, soil testing, etc. This is summarized in total fertility costs. Finally, this is related to scenario yields and to crop prices to arrive at total revenue, and the margin over fertility costs for each scenario.

The agronomic-nitrous oxide model consists of three blocks – Scenario Setup, Emission and Cost Simulation, and Data (Figure 3.2). In the Scenario Setup block, the scenario is specified- Baseline, Basic, or Advanced. Given the scenario specifics the Simulation and Cost Emission block searches for the required data in the dataset, performs the calculations, and displays the results. The N_2O emission calculation is performed for three nitrogen sources such as chemical fertilizer, manure, and crop residue. The dataset contains a region specific data on nitrogen application rates, application methods, timing, type of fertilizers, cost of fertilizers, and nitrogen application costs. The data are given for each crop and order of soil. The following section shows the accounting of N_2O emissions from different nitrogen sources. The model is implemented in Microsoft Excel 2010.

Figure 3.2 Model Layout



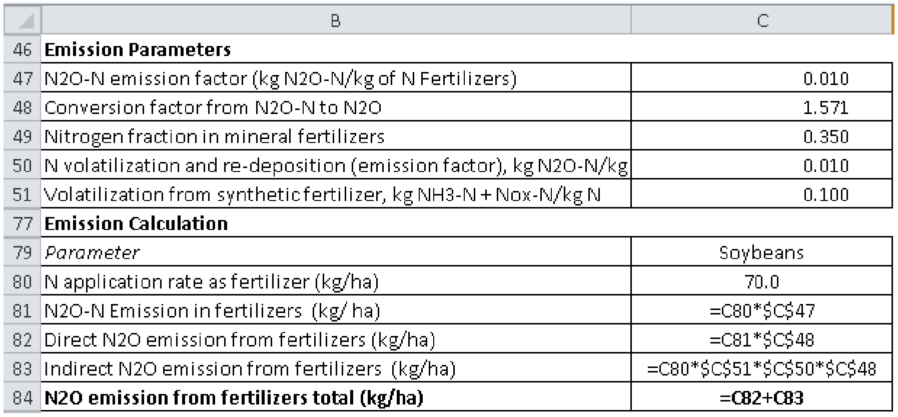
The N_2O emission accounting is based upon the quantification methodology of the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, 2006. This methodology accounts for the direct and indirect N_2O emissions associated with different production technologies. Table 2.3 shows five major equations used for calculating N_2O emissions from commercial fertilizers as well as from other nitrogen sources (IPCC Guidelines for National Greenhouse Gas Inventories, 2006).

Table 2.3 N_2O Accounting Equations

Emission		*Calculation*
Direct N_2O	1.	$N2O\_N = N2O\_N\_emission\_factor \cdot (N\_elemental)$
	2.	$direct\_N2O = N2O\_N \cdot N2O\_N\_to\_N2O\_conversion\_factor$
Indirect N_2O	3.	$NH3\_N = (NH3\_N\_volatilization \cdot N\_elemental)$
	4.	$N2O\_N = NH3\_N \cdot NH3\_to\_N2O\_N\_conversion\_factor$
	5.	$indirect\_N2O = N2O\_N \cdot N2O\_N\_to\_N2O\_conversion\_factor$

Figure 3.3 illustrates the implementation of the equations in the spreadsheet model. The direct N_2O emission is simulated by calculating N_2O-N emission first (C81) and then transformed into the N_2O emission (C82). Indirect N_2O emissions require calculating first the N_2O-N volatilization and re-deposition associated with elemental nitrogen in fertilizers and then transforms it into N_2O (C83) emission using the same approach given for the direct emission calculation. The total N_2O emission is calculated as the sum of direct and indirect emissions (C84).

Figure 3.3 N_2O Emission Accounting from Commercial Fertilizers



	B	C
46	**Emission Parameters**	
47	N2O-N emission factor (kg N2O-N/kg of N Fertilizers)	0.010
48	Conversion factor from N2O-N to N2O	1.571
49	Nitrogen fraction in mineral fertilizers	0.350
50	N volatilization and re-deposition (emission factor), kg N2O-N/kg	0.010
51	Volatilization from synthetic fertilizer, kg NH3-N + Nox-N/kg N	0.100
77	**Emission Calculation**	
79	*Parameter*	Soybeans
80	N application rate as fertilizer (kg/ha)	70.0
81	N2O-N Emission in fertilizers (kg/ ha)	=C80*$C$47
82	Direct N2O emission from fertilizers (kg/ha)	=C81*$C$48
83	Indirect N2O emission from fertilizers (kg/ha)	=C80*$C$51*$C$50*$C$48
84	**N2O emission from fertilizers total (kg/ha)**	**=C82+C83**

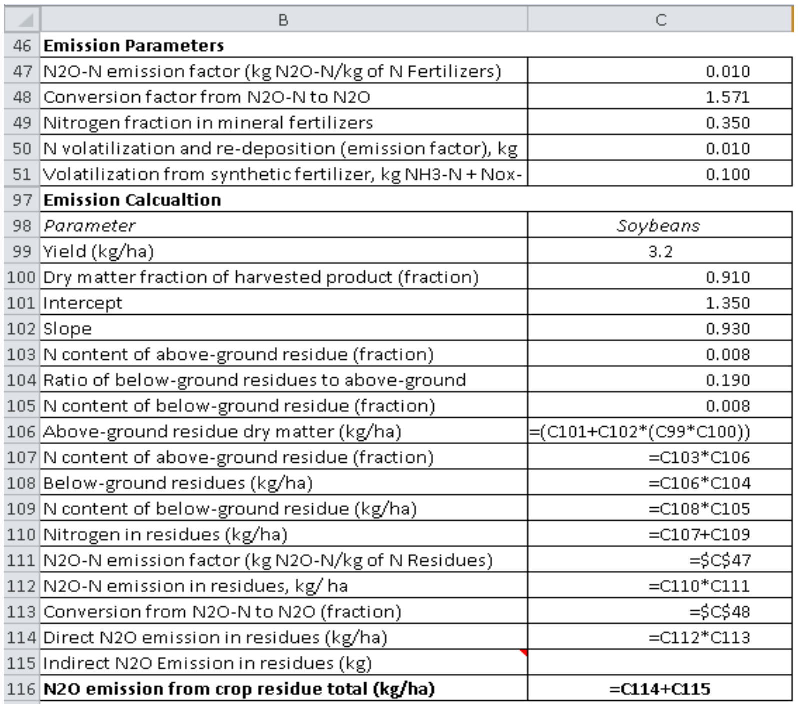
The calculation of N_2O emission from crop residue requires information about nitrogen content in the above- and below-ground crop residue. The calculation of nitrogen content in crop residue is perfumed by a special regression model accepted for this purpose by the IPCC. The model calculates the amount of dry matter in the residue first and then transforms it into elemental nitrogen. The five essential equations of this model are given in Table 3.3.

shows the implementation of the equations and complete N_2O accounting procedure implemented in the spreadsheet model. This procedure does not account for the indirect N_2O emissions. The reason for this is that the indirect emission depends on the water runoff and nutrient leaching information. The latter can only be produced through hydrologic simulation that is out of the scope of this project.

Table 3.3 Calculating of Nitrogen in Crop Residue

N types		*Calculation*
Above ground residue	1.	$above\_ground\_DM = const + slope \cdot (yeild \cdot DM\_content)$
	2.	$N\_above\_ground\_DM = above\_ground\_DM \cdot N\_content\_above\_ground$
Above ground residue	3.	$below\_ground\_DM = above\_ground\_DM \cdot below\_ground\_to\_above\_ground\_ratio$
	4.	$N\_below\_ground\_DM = below\_ground\_DM \cdot N\_content\_below\_ground$
Total N in residue	5.	$N\_residue\_total = N\_above\_ground\_DM + N\_below\_ground\_DM$

Figure 3.4 N_2O Emission Accounting from Crop Residue

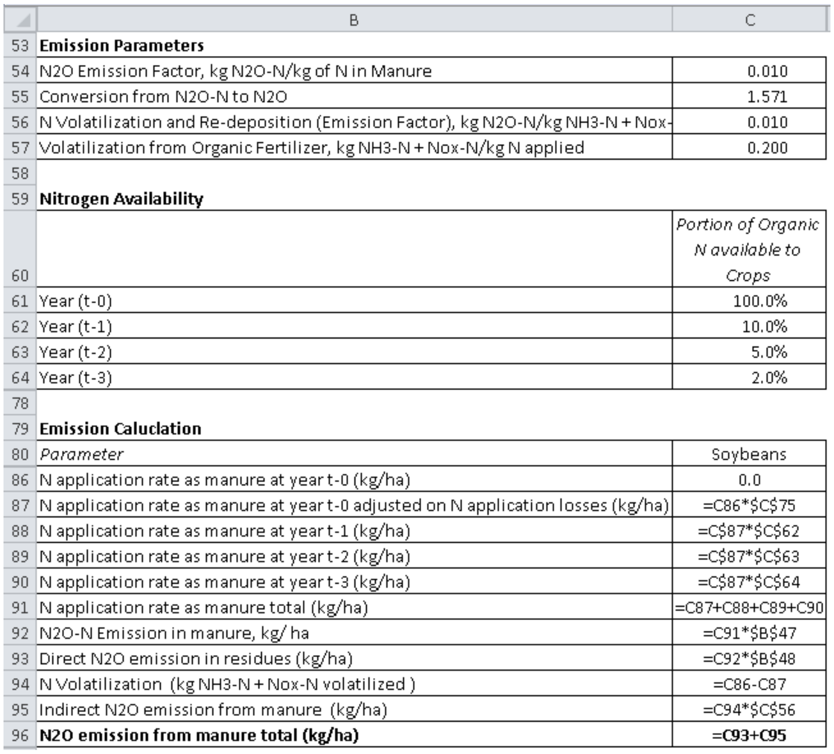


	B	C
46	**Emission Parameters**	
47	N2O-N emission factor (kg N2O-N/kg of N Fertilizers)	0.010
48	Conversion factor from N2O-N to N2O	1.571
49	Nitrogen fraction in mineral fertilizers	0.350
50	N volatilization and re-deposition (emission factor), kg	0.010
51	Volatilization from synthetic fertilizer, kg NH3-N + Nox-	0.100
97	**Emission Calcualtion**	
98	*Parameter*	*Soybeans*
99	Yield (kg/ha)	3.2
100	Dry matter fraction of harvested product (fraction)	0.910
101	Intercept	1.350
102	Slope	0.930
103	N content of above-ground residue (fraction)	0.008
104	Ratio of below-ground residues to above-ground	0.190
105	N content of below-ground residue (fraction)	0.008
106	Above-ground residue dry matter (kg/ha)	=(C101+C102*(C99*C100))
107	N content of above-ground residue (fraction)	=C103*C106
108	Below-ground residues (kg/ha)	=C106*C104
109	N content of below-ground residue (kg/ha)	=C108*C105
110	Nitrogen in residues (kg/ha)	=C107+C109
111	N2O-N emission factor (kg N2O-N/kg of N Residues)	=$C$47
112	N2O-N emission in residues, kg/ ha	=C110*C111
113	Conversion from N2O-N to N2O (fraction)	=$C$48
114	Direct N2O emission in residues (kg/ha)	=C112*C113
115	Indirect N2O Emission in residues (kg)	
116	**N2O emission from crop residue total (kg/ha)**	**=C114+C115**

The model contains a detailed procedure to calculate N_2O emissions from manure applied as fertilizer. It takes the amount of elemental nitrogen in the manure and calculates the direct and indirect N_2O emissions in the way it is implemented in the previous sections. The calculation of the nitrogen in manure uses the dependence of nitrogen availability on manure application year (Figure 3.5). In total it accounts for the nitrogen availability from the manure applied up to three previous years. Another difference is that indirect N_2O emissions from manure depend directly on manure application method, like the broadcast or injection, which may differ for the nitrogen management scenarios. In this way the scenario specification of nitrogen source and place can be reflected in N_2O emission. Figure 3.5 shows the complete procedure for calculation of the N_2O direct and indirect emissions from manure.

The economic cost associated with the Baseline and alternative NERP scenarios is represented by the nitrogen cost. Equation 2–Equation 1 show the procedure used to calculate the nitrogen cost, for a given scenario. The total nitrogen cost is defined as the sum of the cost of elemental nitrogen and the cost of nitrogen application (Equation 1). The cost of elemental nitrogen is calculated by multiplying nitrogen application rate by price of elemental nitrogen (Equation **2**). The cost of nitrogen application depends on a nitrogen application rate and the cost of nitrogen application.

Figure 3.5. Emission Accounting from Manure



	B	C
53	**Emission Parameters**	
54	N2O Emission Factor, kg N2O-N/kg of N in Manure	0.010
55	Conversion from N2O-N to N2O	1.571
56	N Volatilization and Re-deposition (Emission Factor), kg N2O-N/kg NH3-N + Nox-	0.010
57	Volatilization from Organic Fertilizer, kg NH3-N + Nox-N/kg N applied	0.200
58		
59	**Nitrogen Availability**	
60		*Portion of Organic N available to Crops*
61	Year (t-0)	100.0%
62	Year (t-1)	10.0%
63	Year (t-2)	5.0%
64	Year (t-3)	2.0%
78		
79	**Emission Caluclation**	
80	*Parameter*	Soybeans
86	N application rate as manure at year t-0 (kg/ha)	0.0
87	N application rate as manure at year t-0 adjusted on N application losses (kg/ha)	=C86*$C$75
88	N application rate as manure at year t-1 (kg/ha)	=C$87*$C$62
89	N application rate as manure at year t-2 (kg/ha)	=C$87*$C$63
90	N application rate as manure at year t-3 (kg/ha)	=C$87*$C$64
91	N application rate as manure total (kg/ha)	=C87+C88+C89+C90
92	N2O-N Emission in manure, kg/ ha	=C91*$B$47
93	Direct N2O emission in residues (kg/ha)	=C92*$B$48
94	N Volatilization (kg NH3-N + Nox-N volatilized)	=C86-C87
95	Indirect N2O emission from manure (kg/ha)	=C94*$C$56
96	**N2O emission from manure total (kg/ha)**	**=C93+C95**

Equation 1. Total Nitrogen Cost

$$N\_cost\_total = N\_cost\_elemental + N\_cost\_application$$

Equation 2. Cost of elemental Nitrogen

$$N\_cost\_elemental = N\_elemental\_price \cdot N\_application\_rate$$

Equation 3. Cost of Nitrogen application

$$N\_cost\_application = N\_application\_rate \cdot N\_application\_cost$$

Section 4 populates this baseline model structure with data from western Canada and eastern Canada to simulate empirically a baseline. This is then altered to reflect BMP scenarios and the simulations are re-run. The BMP metrics in terms of economics and emissions are then compared with the baseline to assess the impact and feasibility of the BMP scenarios.

3.3 Data

Data for the economic model were obtained for fertilizer ingredient prices, costs of fertility services, crop yields and prices. Crop prices are summarized in Table 3.5. Crop prices represent provincial level five-year averages for the period 2010-14. Fertilizer prices are summarized in Table 3.6. Prices for fertilizer ingredients were obtained from a monthly survey by Alberta Agriculture and Rural Development (AARD), averaged over the period March 2012-February 2015. Pricing for ammonium sulfate in Alberta was from industry sources as of spring 2015, as was the value of urease inhibitor Agrotain, based upon a cost of 8 cents/lb actual nitrogen in treated fertilizer. Ontario fertilizer ingredients data was obtained from the Ridgetown College Ontario Farm Input Monitoring Project, and averaged for May 2012, May 2013, May 2014, and October 2014. Prices for Agrotain-treated UAN in Ontario are based on 8 cents/lb actual nitrogen.

Table 3.6 presents costs for agronomic services. For Alberta, agronomy service costs are based on 2013 survey data collected by Alberta Agriculture and Rural Development. For Ontario, these data were obtained from OMAFRA based on a survey of 2012 custom rates.

Table 3.5 2010-2014 Average Crop Prices

	Alberta		Ontario	
	$/tonne	$/bushel	$/tonne	$/bushel
Canola	505.51	11.47		
Wheat	239.70	6.52	227.63	6.19
Barley	187.91	4.09		
Corn			216.16	5.49

Source: Statistics Canada

Table 3.6 Fertilizer Ingredient Prices

	Alberta	Ontario
Urea	640	638
UAN		422
MAP	742	755
Potash		620
Ammonium Sulfate	425	
Agrotain-treated Urea	721	
Agrotain-treated UAN		465

Table 3.7 Agronomic Service Costs, $/acre

	Alberta, 2013	**Ontario, 2012**
Custom Air Seeder	20-30	24
Spread Dry Fertilizer	7-10	8
Spread Liquid Fertilizer		9
Liquid Side-dress		10
Soil testing- complete analysis plus N, K, S, Ca, Mg on 0-6" and 6-12" ($/field)	$150-175/Field $1/acre based on 160 acres	

4 Results

This section provides an overview of agronomic, economic, and nitrous oxide results.

4.1 Agronomic Results

Based upon the specification of scenarios, the following agronomic results were obtained. Table 4.1 provides a summary of fertilizer recommendations by scenario and soil zone for Alberta, in lbs/acre of actual elemental nutrient, as calculated by the Affirm model. The results show that levels of potassium (K_2O) were generally adequate and did not require supplementary fertilizer. Sulfur was an element of the canola fertility program in each of the soil zones. In all scenarios, the phosphorus application occurred at planting. Under the baseline scenario, nitrogen/sulfur applications were spring broadcast; under the basic and advanced NERP scenarios nitrogen/sulfur was banded at seeding in the spring.

Table 4.2 provides a summary of the agronomic results for Ontario scenarios, based on output from NMAN with yields of 150 bushels/acre for corn and 74 bushels/acre for wheat. Because Ontario conditions do not vary according to soil zone in the same way as in Alberta, the agronomic results are much simpler. In all cases, phosphorus and potash applications occurred with starter fertilizer. Under the baseline scenario nitrogen was surface broadcast in the spring; under the NERP scenarios split applications of nitrogen occurred- split broadcast applications (wheat) and broadcast followed by side dress (corn).

4.2 Economic Results

Table 4.3 below presents the fertilizer costs across soil regions and scenarios for Alberta. For a given crop within a given soil zone, the costs of fertilizer increase for the advanced scenario over the basic scenario, but are about equal for the baseline and basic scenarios. However, when the agronomy service costs are included, the total fertilizer and agronomy costs increase with the NERP scenario, with the basic NERP costs exceeding baseline, and the advanced NERP costs exceeding the basic NERP. Overall, the costs of fertilizer and agronomy, and of the NERP scenarios, was highest for the black soil zone followed by the dark brown soil zone and grey soil zone. These costs per acre were associated with yields and crop revenue by scenario to obtain the margin over total fertilizer and agronomy cost per acre for each scenario. The table shows that the margin over fertilizer and agronomy cost per acre by scenario tracks the yield. That is, the advanced NERP scenarios that have the highest yields provide a greater margin than the basic NERP scenario, which in turn provides a greater margin than the baseline scenario. This is the case despite the fact that total costs of fertilizer and agronomy increase with the level of NERP scenario.

Table 4.1 Fertilizer Rates and Yields for Alberta Scenarios

Scenario	Soil Zone		N Rate (Lbs/Acre)	P_2O_5 Rate (Lbs/Acre)	K_2O Rate (Lbs/Acre)	S Rate (Lbs/Acre)	Yield (bu/ac)
Baseline	Dark Brown	Canola	90	20	0	15	28
		Wheat	80	20	0	0	36
		Barley	70	20	0	0	56
	Black	Canola	100	25	0	15	37
		Wheat	115	25	0	0	54
		Barley	100	25	0	0	81
	Dark Grey Peace	Canola	80	25	0	15	27
		Wheat	100	25	0	0	46
		Barley	25	25	0	0	72
NERP Basic	Dark Brown	Canola	90	20	0	15	32
		Wheat	80	20	0	0	42
		Barley	70	20	0	0	65
	Black	Canola	100	25	0	15	43
		Wheat	115	25	0	0	63
		Barley	100	25	0	0	94.395
	Dark Grey Peace	Canola	80	25	0	15	32
		Wheat	100	25	0	0	54
		Barley	25	25	0	0	84
NERP Advanced	Dark Brown	Canola	85.5	20	0	15	34
		Wheat	76	20	0	0	44
		Barley	66.5	20	0	0	68
	Black	Canola	95	25	0	15	45
		Wheat	109.25	25	0	0	66
		Barley	95	25	0	0	99
	Dark Grey Peace	Canola	76	25	0	15	33
		Wheat	95	25	0	0	56
		Barley	23.75	25	0	0	88

Table 4.2 Fertilizer Rates and Yields for Ontario Scenarios

		N (lbs/acre)	**P_2O_5 Rate (Lbs/Acre)**	**K_2O Rate (Lbs/Acre)**	**Yield (tonnes/acre)**	**Yield (bushels/acre)**
Corn	Baseline	143	55	55	3.81	150
	NERP Basic	129	55	55	3.81	150
	NERP Advanced	129	55	55	4.19	165
Wheat	Baseline	89	46	28	2.00	74
	NERP Basic	130	46	28	2.45	90

Table 4.3 Economic Results- Alberta

	Crop		Fertilizer Ingredient Cost ($/acre)	Fertilizer and Agronomy Cost ($/acre)	Yield (bushels/acre)	Revenue ($/acre)	Margin over Fertilizer and Agronomy Cost ($/acre)
Dark Brown Soils	Canola	Baseline	70.79	79.29	28	318.47	239.18
		Basic NERP	70.79	96.79	32	371.55	274.76
		Advanced NERP	73.40	99.40	34	389.24	289.84
	Wheat	Baseline	60.71	69.21	36	233.64	164.42
		Basic NERP	60.71	86.71	42	272.58	185.86
		Advanced NERP	63.93	89.93	44	285.56	195.62
	Barley	Baseline	54.41	62.91	56	227.94	165.03
		Basic NERP	54.41	80.41	65	265.93	185.52
		Advanced NERP	57.18	83.18	68	278.59	195.41
Black Soils	Canola	Baseline	79.66	88.16	37	424.97	336.81
		Basic NERP	79.66	105.66	43	495.80	390.14
		Advanced NERP	82.63	108.63	45	519.41	410.77
	Wheat	Baseline	85.35	93.85	54	351.63	257.78
		Basic NERP	85.35	111.35	63	410.23	298.88
		Advanced NERP	90.04	116.04	66	429.77	313.73
	Barley	Baseline	75.89	84.39	81	330.51	246.12
		Basic NERP	75.89	101.89	94	385.60	283.71
		Advanced NERP	79.91	105.91	99	403.96	298.05
Grey Soils	Canola	Baseline	67.05	75.55	27	310.20	234.65
		Basic NERP	67.05	93.05	32	361.90	268.85
		Advanced NERP	69.13	95.13	33	379.13	284.00
	Wheat	Baseline	63.28	71.78	46	299.38	227.60
		Basic NERP	63.28	89.28	54	349.28	260.00

		Advanced NERP	66.41	92.41	56	365.91	273.50
	Barley	Baseline	28.60	37.10	72	294.85	257.75
		Basic NERP	28.60	54.60	84	343.99	289.40
		Advanced NERP	29.29	55.29	88	360.37	305.09

Table 4.4 below presents the fertilizer costs by scenario and crop for Ontario. For corn, the baseline fertilizer cost is highest, as both basic and advanced NERP scenarios reduce N application rates by 10%. However, the advanced scenario contains the additional cost of the urease inhibitor Agrotain, which increases the fertilizer cost, almost to the level of the baseline scenario. When the costs of agronomy (trips over the field to apply fertilizer, soil testing, etc.) are included with fertilizer ingredients, the combined cost of fertilizer and agronomy services increases with the intensity of NERP scenarios, with the Advanced scenario exceeding the Basic scenario, which in turn exceeds (slightly) the baseline scenario. The revenue per acre is equal for baseline and basic scenarios, but 10% higher for the advanced scenario. The result is that the advanced scenario provides the largest margin over feed cost, followed by the baseline and the basic NERP scenario.

The wheat scenarios vary considerably according to fertilizer cost, with the basic NERP fertilizer costs about 25% higher than the baseline. When the additional costs associated with split nitrogen applications and fungicide application are factored in, the fertilizer and agronomy costs associated with the basic scenario exceed that of the baseline by almost $73/acre. However, the basic scenario provides for a significant increase in yield, and a corresponding increase in revenue. Revenue under the basic scenario is about $97/acre higher compared with baseline. Thus the margin over fertilizer costs increases under the basic scenario by about $29/acre.

Thus, the NERP scenarios broadly increased production costs, but increased yields and revenue relatively more. With one exception in corn, the basic NERP had a higher margin per acre than the baseline, and the advanced scenario had a higher margin per acre than the basic scenario.

Table 4.4 Economic Results- Ontario

		Fertilizer Ingredient Cost ($/acre)	Fertilizer and Agronomy Cost ($/acre)	Yield tonnes/acre	Revenue $/acre	Margin over Fertilizer and Agronomy Cost $/acre
Corn	Baseline	151.55	159.55	3.81	822.63	663.08
	Basic	141.80	161.80	3.81	822.63	660.83
	Advanced	151.15	171.15	4.19	904.89	733.74
Wheat	Baseline	97.31	105.31	2.00	456.18	350.87
	Basic	125.12	178.03	2.45	557.56	379.15

4.3 Nitrous Oxide Emission Results

Table 4.5 below presents the nitrous oxide emission results for the NERP BMP scenarios in Alberta. The first column of results represents the nitrous oxide emissions associated with fertilizer; the second column gives the emissions associated with crop residue. The total of fertilizer and crop residue emissions is presented in terms of both kilograms emitted per acre and grams emitted per bushel.

In each case, a significant reduction in nitrous oxides is observed in shifting from the baseline to basic scenarios, and from basic to advanced scenarios. In each of the soil zones and for each crop, on the basis of emissions per acre, nitrous oxide emissions decreased by 15% between basic and baseline scenarios and by 28% between advanced and baseline scenarios. On a per bushel basis, the percentage reduction was 27% between basic and baseline scenarios, and 42% between advanced and baseline scenarios. Thus, the emission reductions were very significant.

Table 4.6 presents the nitrous oxide emission reductions for the scenarios explored in Ontario. The basic and advanced scenarios for corn show a significant reduction in nitrous oxide emissions versus the baseline. On a per acre basis, the reduction in emissions for the basic scenario versus the baseline amounted to about 24%; for the advanced scenario versus the baseline the difference amounted to about 39%. The situation was somewhat different for winter wheat. On a per acre basis, the emissions under the basic scenario versus baseline increased markedly, consistent with significantly higher levels of fertilizer applied. However, on a per bushel basis the emissions are very similar, with the basic scenario having emissions about 2% higher than baseline.

Table 4.5 Nitrous Oxide Emissions, Alberta Soil Zones

			Fertilizer kg/acre	Crop Residue kg/acre	Total (kg/acre)	Yield (bushels/acre)	Total (g/bushel)
Dark Brown	Canola	Baseline	0.70658	0.00015	0.70673	28	25.5
		Basic	0.60059	0.00014	0.60073	32	18.6
		Advanced	0.50344	0.00012	0.50356	34	14.9
	Wheat	Baseline	0.62807	0.00019	0.62826	36	17.5
		Basic	0.53386	0.00018	0.53404	42	12.8
		Advanced	0.44750	0.00017	0.44767	44	10.2
	Barley	Baseline	0.54956	0.00020	0.54977	56	9.9
		Basic	0.46713	0.00020	0.46733	65	7.2
		Advanced	0.39156	0.00018	0.39174	68	5.7
Black	Canola	Baseline	0.78509	0.00018	0.78527	37	21.2
		Basic	0.66733	0.00017	0.66749	43	15.5
		Advanced	0.55938	0.00015	0.55953	45	12.4
	Wheat	Baseline	0.90285	0.00027	0.90312	54	16.8
		Basic	0.76742	0.00026	0.76768	63	12.2
		Advanced	0.64328	0.00024	0.64352	66	9.8
	Barley	Baseline	0.78509	0.00028	0.78537	81	9.7
		Basic	0.66733	0.00027	0.66760	94	7.1
		Advanced	0.55938	0.00025	0.55963	99	5.7
Grey	Canola	Baseline	0.62807	0.00014	0.62821	27	23.3
		Basic	0.53386	0.00013	0.53400	32	17.0
		Advanced	0.44750	0.00012	0.44762	33	13.6
	Wheat	Baseline	0.78509	0.00023	0.78532	46	17.1
		Basic	0.66733	0.00022	0.66755	54	12.5
		Advanced	0.55938	0.00021	0.55958	56	10.0
	Barley	Baseline	0.19627	0.00025	0.19653	72	2.7
		Basic	0.16683	0.00025	0.16708	84	2.0
		Advanced	0.13984	0.00023	0.14007	88	1.6

Table 4.6 Nitrous Oxide Emissions, Ontario

		Fertilizer kg/acre	Crop Residue kg/acre	Total (kg/acre)	Yield (bushels/acre)	Total (g/bushel)
Corn	Baseline	1.11972	0.00043	1.1202	150	7.5
	Basic	0.85659	0.00037	0.8570	150	5.7
	Advanced	0.75581	0.00035	0.7562	165	4.6
Winter Wheat	Baseline	0.69983	0.00035	0.7002	74	9.5
	Basic	0.86848	0.00035	0.8688	90	9.7

4.4 Sensitivity Analysis

The economic results above were tested to determine the impact of price extremes in fertilizer and crop outputs. To do so, the minimum and maximum prices over the support for price averages used were substituted, and the analysis re-run. In each case, the per acre differential between the advanced scenarios and the baseline was tested, with the exception of Ontario winter wheat in which case the differential between the basic NERP scenario and baseline was evaluated.

The results are reported below in Tables 4.7 and 4.8. The price extremes of the last five years had relatively little impact on the differential in margin over fertilizer cost between NERP and baseline scenarios. These effects were as anticipated- the benefit of the Advanced NERP scenario increases as the price of fertilizer increases, since these involve a reduction in rate. The exception was Ontario winter wheat in which the NERP scenario involves a higher rate. Variation in crop prices generally had a larger effect than fertilizer prices, and the benefit of NERP scenarios increased with the crop price. In all cases of price extremes, the margin per acre remained higher for the advanced NERP scenario versus baseline and for the basic NERP scenario versus baseline with Ontario winter wheat.

4.5 Interpretation

The results observed above demonstrate that the BMP scenarios are broadly beneficial from both an economic and environmental perspective. Thus, rather than assigning a cost associated with attaining nitrous oxide emission reduction, in fact an economic benefit results. The exception to this is winter wheat in Ontario. Effective nitrous oxide scenarios appear more difficult to develop for winter wheat because nitrogen applications are limited to surface broadcasting (subsurface banding is infeasible), the experience has been that yield increases from split nitrogen applications only occur at higher levels of nitrogen applications, and the experience with winter wheat in Ontario to date has not shown positive yield results with urease inhibitors.

Table 4.7 Sensitivity of Spread Between Advanced NERP and Baseline to Price/Cost Changes, Alberta Soil Zones, $/acre

Soil Zone	Crop		Total Fertilizer+ Agronomy Cost/acre Advanced vs Baseline	Revenue $/acre- Advanced vs Baseline	Margin over Fertilizer Cost Advanced vs Baseline
Dark Brown	Canola	Base	20.11	70.77	50.66
		High fertilizer cost	19.27	70.77	51.51
		Low fertilizer cost	20.60	70.77	50.17
		High crop price	20.11	80.45	60.33
		Low crop price	20.11	58.37	38.26
	Wheat	Base	20.72	51.92	31.20
		High fertilizer cost	19.96	51.92	31.95
		Low fertilizer cost	21.15	51.92	30.77
		High crop price	20.72	61.24	40.52
		Low crop price	20.72	43.82	23.11
	Barley	Base	20.27	50.65	30.38
		High fertilizer cost	19.61	50.65	31.04
		Low fertilizer cost	20.66	50.65	30.00
		High crop price	20.27	64.45	44.17
		Low crop price	20.27	37.22	16.94
Black	Canola	Base	20.47	94.44	73.96
		High fertilizer cost	19.53	94.44	74.91
		Low fertilizer cost	21.02	94.44	73.42
		High crop price	20.47	107.35	86.88
		Low crop price	20.47	77.90	57.42
	Wheat	Base	22.19	78.14	55.95
		High fertilizer cost	21.11	78.14	57.03
		Low fertilizer cost	22.82	78.14	55.32
		High crop price	22.19	92.16	69.97
		Low crop price	22.19	65.96	43.77
	Barley	Base	21.52	73.45	51.92
		High fertilizer cost	20.58	73.45	52.87
		Low fertilizer cost	22.07	73.45	51.38
		High crop price	21.52	93.45	71.93
		Low crop price	21.52	53.97	32.44
Grey	Canola	Base	19.58	68.93	49.35
		High fertilizer cost	18.83	68.93	50.10
		Low fertilizer cost	20.02	68.93	48.91
		High crop price	19.58	78.36	58.77

		Low crop price	19.58	56.86	37.27
	Wheat	Base	20.63	66.53	45.89
		High fertilizer cost	19.88	66.53	46.65
		Low fertilizer cost	21.07	66.53	45.46
		High crop price	20.63	78.47	57.83
		Low crop price	20.63	56.16	35.52
	Barley	Base	18.19	65.52	47.33
		High fertilizer cost	17.95	65.52	47.57
		Low fertilizer cost	18.32	65.52	47.20
		High crop price	18.19	83.37	65.18
		Low crop price	18.19	48.14	29.96

Table 4.8 Sensitivity of Spread Between Advanced NERP and Baseline to Price/Cost Changes, Ontario Corn and Winter Wheat

		Total Fertilizer+ Agronomy Cost/acre Advanced vs Baseline	Revenue $/acre- Advanced vs Baseline	Margin over Fertilizer Cost Advanced vs Baseline
Corn	Base Run	11.74	82.26	70.52
	High Fertilizer Cost	10.69	82.26	71.57
	Low Fertilizer Cost	12.42	82.26	69.84
	High Crop Price	11.74	97.03	85.29
	Low Crop Price	11.74	62.70	50.96
Wheat	Base Run	72.71	101.37	28.67
	High Fertilizer Cost	75.70	101.37	25.67
	Low Fertilizer Cost	70.75	101.37	30.62
	High Crop Price	74.05	115.99	41.94
	Low Crop Price	70.58	78.20	7.62

5 Conclusions

The purpose of this this study was to provide an analysis of feasible agronomic scenarios consistent with the NERP implemented under the 4R principles, based on economic and environmental criteria. Drawing from the literature and expert opinion, baseline scenarios were developed along with NERP BMP scenarios for western Canadian crop conditions (based on Alberta) and for eastern Canadian conditions (based on Ontario). The NERP/BMP scenarios were compared against baselines for canola, wheat, and barley for the Dark Brown, Black, and Dark Gray/Peace River soil zones in Alberta, and for corn and winter wheat scenarios in Ontario.

The results showed the following:

- In all cases, the costs of overall fertility management are lowest under the baseline scenario and the highest for the Advanced NERP, followed by the Basic NERP
- The margin over fertility cost was generally the highest for the Advanced NERP, followed by the Basic NERP, followed by the baseline. The exceptions were corn in which the Basic scenario had lower returns compared with the baseline, and winter wheat in which an Advanced scenario was not developed
- The economic benefit of the NERP scenarios was material. For example, the differential returns from Advanced versus baseline scenarios ranged from $29/acre to $71/acre
- The nitrous oxide emission reduction effects observed were material. On a per acre basis, the Advanced scenario reduced emissions by about 29% versus baseline for western Canada, and the advanced scenario for Ontario corn reduced nitrous oxide emissions by about 33% versus baseline
- With only one exception, strategies to mitigate nitrous oxides and to increase returns per acre are consistent with one another. That is, the scenarios that decreased nitrous oxide emissions the most were the most profitable
- NERP scenarios that were both economically feasible and efficacious in reducing nitrous oxides for Ontario winter wheat were difficult to isolate. The basic NERP scenario for winter wheat had a higher per acre margin over fertility cost, but larger nitrous oxide emissions than the baseline on a per acre basis. When the increased yield, the emissions on a per bushel basis were similar for baseline and basic NERP scenarios.

These results suggest that while NERP practices are likely to increase costs, the benefits exceed the additional costs. In no case were the margins/acre over fertility cost higher under the baseline than under the Advanced NERP scenarios.

Table 5.1 below extrapolates the prospective benefits from the results for western and eastern Canada. For the west, the table shows the results for a farm of 960 acres growing canola, wheat and barley in a continuous rotation of the three crops. For the purposes of illustration, it shows the implied benefit for an Ontario farm growing 320 acres of corn. The table shows that for a western farm growing the three crops, the benefits could range between $34,516 and $56,457 per farm. For Ontario, based on corn alone, the prospective could be $22,611.

Table 5.1 Prospective Individual Farm Benefits of Advanced NERP vs. Baseline

		Advanced NERP-Baseline	Acres/year	$/Year	Total $/Farm
Alberta- Dark Brown	Canola	48.62	320	15,557	34,517
	Wheat	28.87	320	9,239	
	Barley	30.38	320	9,721	
Alberta- Black	Canola	71.24	320	22,797	56,194
	Wheat	52.44	320	16,782	
	Barley	51.92	320	16,616	
Alberta-Dark Gray Peace	Canola	47.36	320	15,155	56,457
	Wheat	63.54	320	20,334	
	Barley	65.52	320	20,967	
Ontario Corn		70.66	320	22,611	22,611

References

Asgedom, H. and Kebreab, E. 2011. Beneficial management practices and mitigation of greenhouse gas emissions in the agriculture of the Canadian Prairie: a review. Agronomy for Sustainable Development. 31: 433-451.

Ausubel, Jesse H, Iddo K. Wernick, and Paul E. Waggoner. "Peak Farmland and the Prospect for Land Sparing", *Population and Development Review* 38 Supplement. 221-242. 2012.

Badiou, P., McDougal, R., Pennock, D., and Clark, B. 2011. Greenhouse gas emissions and carbon sequestration potential in restored wetlands of the Canadian prairie pothole region. Wetlands Ecol. Manage. 19: 237-256.

Baker, Justin S. Brian C. Murray, Bruce A. McCarl, Siyi Feng, and Robert Johansson. "Implications of Alternative Agricultural Productivity Growth Assumptions on Land Management, Greenhouse Gas Emissions, and Mitigation Potential", *American Journal of Agricultural Economics* 95(2) 435-441. 2013.

Beauchemin, K.A., Janzen, H.H., Little, S.M., McAllister, T.A., McGinn, S.M. 2010. Life cycle assessment of greenhouse gas emissions from beef production in western Canada: A case study. Agricultural Systems 103: 371-379.

Bedard-Haughn, A., Yongbloed. F., Akkerman, J., Uijl, A., de Jong, E., Yates, T., Pennock, D. 2006. The effects of erosional and management history on soil organic carbon stores in ephemeral wetlands of hummocky agricultural land-scapes. Geoderma 135: 296-306

Benton, T. G., Vickery, J. A. and Wilson, J. D. 2003. Farmland biodiversity: is habitat heterogeneity the key? Trends in Ecology & Evolution. 18: 182-188.

Beres, B. L., Harker, K. N., Clayton, G. W., Bremer, E., O'Donovan, T. T., Blackshaw, R. E. and Smith, A. M. 2010. Influence of N fertilization method on weed growth, grain yield and grain protein concentration in no-till winter wheat. Canadian Journal of Plant Science. 90: 637-644.

Blackshaw, R. E., Hao, X., Brandt, R. N., Clayton, G. W., Harker, K. N., O'Donovan, J. T., Johnson, E. N. and Vera, C. L. 2011. Canola response to ESN and urea in four-year no-till cropping system. Agron. J. 103: 92-99.

Bole, J. B., Harapiak, J. T., Malhi, S. S. and Penny, D. C. 1984. Regional and environmental influences of nitrogen use efficiency. Proc. Alberta Soils Science Workshop. Edmonton, AB.

Bos, J. Smit, A. L.; and Schröder, J. J. 2013. Is agricultural intensification in The Netherlands running up to its limits? NJAS - Wageningen Journal of Life Sciences 66: 65-73.

Bouwman, A. F., Boumans, L. J. M. and Batjes, N. H. 2002. Emissions of N_2O and NO from fertilized fields: summary of available measurement data. Global Biogeochem. Cycles 16: 6-1–6-13.

Bridgham, S.D., Megonigal, J.P., Keller, J.K., Bliss, N.B., and Trettin, C. 2006. The carbon balance of North American wetlands. Wetlands 26: 889–916

Burney, Jennifer A., Steven J. Davis and David B. Lobell. “Greenhouse gas mitigation by agricultural intensification”, *Proceedings National Academies of Sciences* 107 (26) 12052-12057. 2010.

Burton, D. L., Li, X. and Grant, C. A. 2008. Influence of fertilizer nitrogen source and management practice on N2O emissions from two Black Chernozemic soils. Can J. Soil Sci. 88: 219-227.

Campbell, C. A., Janzen, H. H., Paustian, K., Gregorich, E. G., Sherrod, L., Liang, B. C. and Zentner, R. P. 2005. Carbon storage in soils of the North American Great Plains: Effect of cropping frequency. Agron. J. 97: 349-363.

Canadian Fertilizer Institute. 2014. Fertilizer Shipments Survey – July 2013 to March 2014. http://www.cfi.ca/_documents/21-022-x2014001-eng.pdf

Climate Check. 2008. Science Discussion Document for Nitrous Oxide Emission Reduction Protocol. http://carbonoffsetsolutions.climatechangecentral.com/files/microsites/OffsetProtocols/ABProtocolDevelopmentWorkshops/NitrousOxideReduction09/SCIENCE_DISCUSSION_DOCUMENT_NERP_WORKSHOP.pdf

Davies, B., Baulcombe, D., Crute, I., Dunwell, J., Gale, M., Jones, J. and Toulmin, C. 2009. Reaping the benefits: science and the sustainable intensification of global agriculture.

Decock, C. 2014. Mitigating nitrous oxide emissions from corn cropping systems in the midwestern U.S.: potential and data gaps. Environ Sci Technol. 48: 4247-4256.

Euliss Jr., N.H., Gleason, R.A., Olness, A., McDougal, R.L., Murkin, H.R., Robarts, R.D., Bourbonniere, R.A., Warner, B.G. 2006. North American prairie wetlands are important nonforested land-based carbon storage sites. Science of the Total Environment 361: 179–188.

Farmaha, B. S. and Sims, A. L. 2013. The influence of polymer-coated urea and urea fertilizer mixtures on spring wheat protein concentrations and economic returns. Agronomy Journal. 105: 1328-1334.

Firbank, L. G., Elliott, J., Drake, B., Cao, Y. and Gooday, R. 2013. Evidence of sustainable intensification among British farms. Agriculture, Ecosystems and Environment. 173: 58-65

Foley, J. 2014. A Five-Step Plan to Feed the World. National Geographic. 225(5): 26-58

Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., and Zaks, D. P. M. 2011. Solutions for a cultivated planet. Nature. 478: 337-342.

Gao, X., Tenuta, M., Nelson, A., Sparling, B., Tomasiewicz, D., Mohr, R. M. and Bizimungu, B. 2013. Effect of nitrogen fertilizer rate on nitrous oxide emission from irrigated potato on a clay loam soil in Manitoba, Canada. Can. J. Soil Sci. 93: 1-11.

Gelfand, I., Zenone, T., Jasrotia, P., Chen, J., Hamilton, S.K., Robertson, G.P. 2011. Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production. Proc. Natl. Acad. Sci. USA 108, 13864–13869

Gleason, R.A., Laubhan, M.K., and Euliss, N.H., Jr., eds., 2008, Ecosystem services derived from wetland conservation practices in the United States Prairie Pothole Region with an emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs: U.S. Geological Professional Paper 1745, 58 p.

Goodale, C.L., Apps, M.J., Birdsey, R.A., Field, C.B., Heath, L.S., Houghton, R.A., Jenkins, J.C. Kohlmaier, G.H., Kurz, W., Liu, S., Nabuurs, G., Nilsson, S. and Shvidenko, A.Z. 2002. Forest carbon sinks in the northern hemisphere. Ecological Applications 12: 891-899.

Grant, C. A. 2014. Use of NBPT and ammonium thiosulphate as urease inhibitors with varying surface placement of urea and urea ammonium nitrate in production of hard red spring wheat under reduced tillage management. Can. J. Plant Sci. 94: 329-335.

Grant, C. A., and Bailey, L. D. 1999. Effect of seed-placed urea fertilizer and N-(n-butyl) thiophosphoric triamide (NBPT) on emergence and grain yield of barley. Can. J. Plant Sci. 79: 491-496.

Grant, C. A., Brown, K. R., Racz, G. J. and Bailey, L. D. 2002. Influence of source, timing and placement of nitrogen fertilization on seed yield and nitrogen accumulation in the seed of canola under reduced- and conventional-tillage management. Can. J. Plant Sci. 82: 629-638.

Grant, C. A., Brown, K. R., Racz, G. J. and Bailey. L. D. 2001. Influence of source, timing and placement of nitrogen on grain yield and nitrogen removal of durum wheat under reduced- and conventional-tillage management. Can. J. Plant Sci. 81: 17-27.

Grant, C. A., Wu, R., Selles, F., Harker, K. N., Clayton, G. W., Bittman, S., Zebarth, B. J. and Lupwayi, N. Z. 2012. Crop yield and nitrogen concentration with controlled release urea and split applications of nitrogen as compared to non-coated urea applied at seeding. Field Crop. Res. 127: 170-180.

Grant, R. F., Pattey, E., Goddard, T. W., Kryzanowski, L. M., Puurveen, H. 2006. Modeling the effects of fertilizer application rate on nitrous oxide emissions. Soil Sci. Soc. Am. J. 70: 235-248.

Guo, L. B. and Gifford, R. M. 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology. 8: 345–360. doi:10.1046/j.1354-1013.2002.00486.x

Gutierrez-Velez, V. H., DeFries, R., Pinedo-Vasquez, M., Uriarte, M., Padoch, C., Baethgen, W., Fernandes, K. and Lim, Y. 2011. High-yield oil palm expansion spares land at the expense of forests in the Peruvian Amazon. Environmental Research Letters. 6: 044029.

Haderlein, L., Jensen, T. L., Dowbenko, R. E. and Blaylock, A. D. 2001. Controlled release urea as a nitrogen source for spring wheat in western Canada: Yield, grain N content and N use efficiency. The Scientific World Journal. 1: 114-121.

Halvorson, A. D., and Bartolo, M. E. 2014a. Nitrogen source and rate effects on irrigated corn yields and nitrogen-use efficiency. Agron. J. 106: 681-693.

Halvorson, A. D., Snyder, C.S., Blaylock, A. D. and Del Grosso, S. J. 2014b. Enhance deficiency nitrogen fertilizers: Potential role in nitrous oxide emission mitigation. Agron. J. 106: 715-722.

Harapiak, J. T. 1979. Comparison of fall and spring applied nitrogen. p.37-43. In Proc. Alberta Soil Science Workshop, Lethbridge, AB. 26–27 Feb. 1979. Faculty of Extension, Univ. of Alberta, Edmonton, AB.

Harvey, M., and Pilgrim, S. 2011. The new competition for land: food, energy, and climate change. Food Policy. 36: S40-S51.

Hoben, J. P., Gehl, R. J., Millar, N., Grace, P. R., Robertson, G. P. 2011. Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the U.S. Midwest. Global Change Biol. 17: 1140-1152.

Holzapfel, C. B., Lafond, G. P., Brandt, S. A., May, W. E. and Johnston, A. M. 2007. In-soil banded versus post-seeding liquid nitrogen applications on no-till spring wheat and canola. Can. J. Plant Sci. 87: 223-232.

Hutchinson, J.J., Campbell, C.A., and Desjardins, R.L. 2007. Some perspectives on carbon sequestration in agriculture. Agric. Forest. Met. 142: 288-302.

Hyatt, C. R., Venterea, R. T., Rosen, C. J., McNearney, M., Wilson, M. L. and Dolan, M. S. 2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. Soil Sci. Soc. Am. J. 74: 419-428.

Ingle, H. L., Koenig, R. T. and Stowe, M. S. 2010. Effect of seed-row placement of conventional and polymer-coated urea on winter wheat emergence. Communications in Soil Science and Plant Analysis. 41: 887-896.

IPNI. 2010. Soil test levels in North America. International Plant Nutrition Institute. http://www.ipni.net/ipniweb/portal.nsf/0/C13F0CF310F1903E062577C7005A4BD7

IPNI. 2012. 4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition, North American Version, Eds. Bruulsema, T. W., Fixen, P. E. and Sulewski, G.D. International Plant Nutrition Institute, Norcross, GA. USA.

Janzen, H. H., Desjardins, R. L., Rochette, P., Boehm M. and Worth, D. 2008. Better farming better air: a scientific analysis of farming practices and greenhouse gases in Canada. Agriculture and Agri-Food Canada. http://publications.gc.ca/collections/collection_2009/agr/A52-83-2008E.pdf

Johnson, J. M. F., Reicosky, D.C., Allmaras, R. R. and Sauer, T. J. (2005). Greenhouse Gas Contributions and Mitigation Potential of Agriculture in the Central USA. Soil & Tillage Research. 83: 73-94.

Johnson, J. W., Murrell, T. S., Reetz Jr., H. F. 1997. Balanced fertility management: a key to nutrient use efficiency. Better Crops. 81: 3-5.

Johnston, A. M., Lafond, G. P., Harapiak, J. T. and Head, W. K. 1997. No-till spring wheat and canola response to side banded anhydrous ammonia at seeding. J. Prod. Agric. 10: 452-458.

Johnson, Peter. Personal communication April 2015.

Johnson, Peter. 2013. “Assessing the Benefits of Agrotain Plus on Winter Wheat”, Crop Advances Field Crop Reports Vol. 10-2013. Ontario Soil and Crop Improvement Association.

Karamanos, R. E., Flore N. A. and Harapiak, J. T. 2005. Effect of post-emergence nitrogen application on the yield and protein content of wheat. Can. J. Plant Sci. 85: 327-342.

Karamanos, R. E., Harapiak, J. T., Flore, N. A. and Stonehouse, T. B. 2004. Use of N-(n-butyl) thiophosphoric triamide (NBPT) to increase safety of seed-placed urea. Can. J. Plant Sci. 84: 105-116.

Karamanos, R., McKenzie. R. H., Gan, Y. T., Lafond, G. P., Jones, C. A. and Malhi S. S. 2010. Fertilizer management for maximum yield of common crops in the Northern Great Plains of North America. pp 33–72. In: Malhi, S. S., Gan, Y. T., Schoenau, J. J., Lemke, R. L., Liebig, M. A. (eds) Recent trends in soil science and agronomy research in the Northern Great Plains of North America. Research Signpost, Kerala, p 427

Kastner, T., Rivas, M. J. I., Koch, W., Nonhebel, S. 2012. Global changes in diets and consequences for land requirements for food. Proceedings of the National Academy of Sciences. 109: 6868-6872.

Khakbazan, M., Grant, C. A., Finlay, G., Wu, R., Malhi, S. S., Selles, F., Clayton, G. W., Lupwayi, N. Z., Soon, Y. K. and Harker, K. N. 2013. An economic study of controlled release urea and split applications of nitrogen as compared with non-coated urea under conventional and reduced tillage management. Can. J. Plant Sci. 93: 523-534.

Kim, D.G., Hernandez-Ramirez, G. and Giltrap, D. 2012. Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis. Agric. Ecosyst. Environ. 168: 53-65.

Korol, M. 2004. Fertilizer and pesticide management in Canada. Farm Environmental Management in Canada. Catalogue no. 21-021-MIE, http://www.statcan.ca/english/freepub/21-021-MIE/free.htm.

Kucey, R. M. N. 1986. Effect of fertilizer form, method and timing of application on barley yield and N uptake under dryland conditions in southern Alberta. Can. J. Soil Sci. 66: 615-621.

Kucey, R. M. N. and Schaalje, G. B. 1986. Comparison of nitrogen fertilizer methods for irrigated barley in the northern great plains. Agron. J. 78: 1091-1094.

Lafond, G. P., Brandt, S. A., Irvine, B., May, W. E. and Holzapfel, C. B. 2008. Reducing the risks of in-crop nitrogen fertilizer applications in spring wheat and canola. Can. J. Plant Sci. 88: 907-919.

Li, C., Hao, X., Blackshaw, R. E., O'Donovan, J. T., Harker, K. N., Clayton, G. W. 2012. Nitrous oxide emissions in response to ESN and urea, herbicide management and canola cultivar in a no-till cropping system. Soil and Tillage Research. 118: 97-106.

Luyssaert S, Inglima I, Jung M et al. 2007. CO2 balance of boreal, temperate, and tropical forests derived from a global database. Glob. Change Biol. 13: 2509–2537.

Ma, B. L., Wu, T. Y., Tremblay, N., Deen, W., Morrison, M. J., Mclaughlin, N. B., Gregorich, E. G. and Stewart, G. 2010. Nitrous oxide fluxes from corn fields: on-farm assessment of the amount and timing of nitrogen fertilizer. Glob. Change Biol. 16: 156-170.

MAFRI. 2014. Guidelines for estimating crop production costs 2014. http://www.gov.mb.ca/agriculture/business-and-economics/financial-management/pubs/cop_crop_productionwesternmb.pdf

Malhi, S. S. and Lemke, R. L. 2013. Effectiveness of Seedrow-placed N with polymer-coated and NBPT-treated urea for canola and wheat. J. Plant Nutr. 36: 2205-2224.

Malhi, S. S. and Nyborg, M. 1990a. Efficiency of fall-applied urea for barley: influence of date of application. Fert. Res. 22: 141-145.

Malhi, S. S. and Nyborg, M. 1990b. Evaluation of methods of placement for fall-applied urea under zero tillage. Soil Tillage Res. 15: 383-389.

Malhi, S. S. and Nyborg, M. 1988a. Effect of ATC, N-Serve 24E and thiourea nitrification inhibitors on yield and N uptake of barley fertilized with fall-applied N. Plant Soil. 105: 223-229.

Malhi, S. S. and Nyborg, M. 1988b. Control of nitrification of fertilizer nitrogen: effect of inhibitors, banding and nesting. Plant Soil. 107: 245-250.

Malhi, S. S. and Nyborg, M. 1984. Inhibiting nitrification and increasing yield of barley by band placement of thiourea with fall appliedurea. Plant Soil 77: 193-206.

Malhi, S. S. and Nyborg, M. 1983. Release of mineral N from soils: influence of inhibitors of nitrogen. Soil Biol. Biochem. 15: 581-585.

Malhi, S. S., and McGill, W. B. 1982. Nitrification in three Alberta soils: Effect of temperature, moisture and substrate concentration. Soil Biol. Biochem.14: 393-399.

Malhi, S. S. and Nyborg, M. 1979. Nitrate formation during winter from fall-applied urea. Soil Biol. Biochem. 11: 439-441.

Malhi, S. S., Soon, Y. K., Grant, C. A. Lemke, R. and Lupwayi, N. 2010. Influence of controlled-release urea on seed yield and N content, and N use efficiency of small grain crops grown on Dark Gray Luvisols. Can. J. Soil Sci. 90: 363-372.

Malhi, S. S., Oliver, E., Mayerle, G., Kruger, G. and Gill, K. S. 2003. Improving effectiveness of seedrow placed urea with urease inhibitor and polymer coating for durum wheat and canola. Communications in Soil Science and Plant Analysis 34: 1709-1727.

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 Res. 60: 101-122.

Malhi, S. S., Nyborg, M., Solberg, E. D. and Heaney, D. J. 1992. Fall compared to spring application of nitrogen fertilizers in Alberta. Technical Bulletin 8E. Research Branch Agriculture Canada, Lacombe, AB.

Malhi, S. S., Nyborg, M. and Solberg, E. D. 1990. Potential for nitrate-N loss in central Alberta soils. Fert. Res. 25: 175-178.

Malhi, S. S., Nyborg, M., Harapiak, J. T. and Penny, D. C. 1984. Efficiency of fall-applied N as influenced by methods of placement and date of fall application. Proc. Alberta Soil Science Workshop, Agriculture Secretary, University of Alberta, Edmonton, AB.

Matson, P. A., Parton, W. J., Power, A. G. and Swift, M. J. 1997. Agricultural intensification and ecosystem properties. Science. 277: 504-509.

Mattison, E. H. and Norris, K. 2005. Bridging the gaps between agricultural policy, land-use and biodiversity. Trends in Ecology & Evolution. 20: 610-616.

McKenzie, R. H., Bremer, E., Middleton, A. B., Pfiffner, P. G. and Dowbenko, R. E. 2007. Controlled-release urea for winter wheat in southern Alberta. Can. J. Soil Sci. 87: 85-91.

McKenzie, R. H., Middleton, A. B., and Pfiffner, P. G. 2010. Evaluation of polymer-coated urea and urease inhibitor for winter wheat in Southern Alberta. Agron. J. 102: 1210-1216.

Monreal, C., McGill, W. B. and Nyborg, M. 1986. Spatial heterogeneity of substrates: effects on hydrolysis, immobilization and nitrification of urea-N. Can. J. Soil Sci. 66: 499-511.

Mullen, R. and Lentz, E. 2011. Nitrogen inhibitors, what is what and should you consider their use? C.O.R.N Newsletter 2011-08. Ohio State University.
http://corn.osu.edu/newsletters/2011/2011-08-1

Mussell, Al, and Dan Heaney. 2013. An Economic Analysis of Farming4RLand program in Alberta. George Morris Centre.
http://www.farming4rfuture.ca/assets/4R_economicanalysis_report.pdf

National Inventory Report 1990–2011: Greenhouse Gas Sources and Sinks in Canada, Part 3. Spurces and Sinks in Canada. http://publications.gc.ca/site/eng/443225/publication.html

Nyborg, M. and Malhi, S. S. 1992. Effectiveness of fall- versus spring-applied urea on barley: pellet size and depth of placement. Fert. Res. 31: 235-239.

Nyborg, M. and Malhi, S. S. 1986. Comparison of fall and spring application of nitrogen fertilizers in northern and central Alberta. Can. J. Soil Sci. 66: 225-236.

Nyborg, M. and Leitch, R. H. 1979. Losses of soil and fertilizer nitrogen in northern Alberta – a review. Proc. Alberta Soil Science Workshop. Lethbridge, AB.

Nyborg, M., Laidlaw, J. W., Solberg, E. D. and Malhi, S. S. 1997. Denitrification and nitrous oxide emissions from a black chernozemic soil during spring thaw in Alberta. Can. J. Soil Sci. 77: 153-160.

Nyborg, M., Malhi, S. S. and Solberg, E. D. 1990. Effect of date of application on the fate of 15N-labelled urea and potassium nitrate. Can. J. Soil Sci. 70: 21-31.

Olewiler, N. 2004. The Value of Natural Capital in Settled Areas of Canada. Published by Ducks Unlimited Canada and the Nature Conservancy of Canada. 36 pp.

Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA). 2009. *Agronomy Guide for Field Crop Production***,** Publication 811. Toronto: Queen's Printer for Ontario.

Parkin, T. B., and Hatfield, J. L. 2014. Enhanced efficiency fertilizers: Effect on nitrous oxide emissions in Iowa. Agron. J. 106: 694-702

Pennock, D., Yates, T., Bedard-Haughn, A., Phipps, K., Farrell, R., McDougal, R. 2010. Landscape controls on N2O and CH4 emissions from freshwater mineral soil wetlands of the Canadian Prairie Pothole region. Geoderma 155: 308–319.

Phalan, B., Bertzky, M., Butchart, S. H. M., Donald, P. F., Scharlemann, J. P. W., Stattersfield, A. J. and Balmford, A. 2013. Crop Expansion and Conservation Priorities in Tropical Countries. PLoS ONE 8: e51759. doi:10.1371/journal.pone.0051759.

Phalan, B., Onial, M., Balmford, A. and Green, R. E. 2011 **Reconciling food production and biodiversity conservation: land sharing and land sparing compared.** *Science* 2. 333: 1289-1291.

Phillips, R. and Beeri, O. 2008. The role of hydropedologic vegetation zones in greenhouse gas emissions for agricultural wetland landscapes. Cantena 72:386–394

Ramankutty, N. and Rhemtulla, J. 2012. Can intensive farming save nature? Frontiers in Ecology and the Environment. 10: **455.**

Rawluk, C. D. L., Grant, C. A. and Racz, G. J. 2001. Ammonia volatilization from soils fertilized with urea and varying rates of urease inhibitor NBPT. Can. J. Soil Sci. 81: 239-246.

Risk, N., Snider, D. and Wagner-Riddle, C. 2013. Mechanisms leading to enhanced soil nitrous oxide fluxes by freeze-thaw cycles. Can. J. Soil Sci. 93: 401-414.

Robertson, G.P., E.A. Paul, and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science 289: 1922–1925.

Rochette, P., MacDonald, J. D., Angers, D. A., Chantigny, M. H., Gasser, M. O. and Bertrand, N. 2009. Banding of urea increased ammonia volatilization in a dry acidic soil. Journal of Environmental Quality. 38: 1383-1390.

Rochette, P., Worth, D. E., Lemke, R. L., McConkey, B. G., Pennock, D. J., Wagner-Riddle, C. and Desjardins, R. L. 2008a. Estimation of N_2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. Can. J. Soil. Sci. 88: 641-654.

Rochette, P., Worth, D. E., Huffman, E. C., Brierley, J. A., McConkey, B. G., Yang, J., Hutchinson, J. J., Desjardins, R. L., Lemke, R. and Gameda, S. 2008b. Estimation of N_2O

emissions from agricultural soils in Canada. II. 1995-2005 inventory. Can. J. Soil Sci. 88: 655-669.

Rudel, T. K., Schneider, L., Uriarte, M., Turner, B. L., DeFries, R., Lawrence, D. and Grau, R. 2009. Agricultural intensification and changes in cultivated areas, 1970–2005. Proceedings of the National Academy of Sciences. 106: 20675-20680.

Saggar, S., Singh, J., Giltrap, D. L., Zaman, M., Luo, J., Rollo, M., Kim, D. G., Rys, G. and van der Weerden, T. J. 2013. Quantification of reductions in ammonia emissions from fertiliser urea and animal urine in grazed pastures with urease inhibitors for agriculture inventory: New Zealand as a case study. Science of the Total Environment. 465: 136-146.

Sistani, K. R., Jn-Baptiste, M., Lovanh, N. and Cook, K. L. 2011. Atmospheric emissions of nitrous oxide, methane, and carbon dioxide from different nitrogen fertilizers. J. Environ. Qual. 40: 1797-1805.

Smith, E. G. 2013. Survey of canola growers: practices, inputs, and production. Presentation at Soils and Crops Conference, March 5-6, 2013. Saskatoon, Saskatchewan. http://www.usask.ca/soilsncrops/conference-proceedings/2013%20pdf/Day_2_Presentations/001-Elwin_Smith.pdf

Smith, E. G., Upadhyay, B. H., Favret, M. L. and Karamanos, R. E. 2010. Fertilizer response for hybrid and open-pollinated canola and economic optimal nutrient levels. Can. J. Plant Sci. 90: 305-310.

Smith, W. K., Cleveland, C. C., Reed, S. C. and Running, S. W. 2014. Agricultural conversion without external water and nutrient inputs reduces terrestrial vegetation productivity. Geophysical Research Letters. 41: 449-455.

Snyder, C. S. and Fixen, P. E. 2012. Plant nutrient management and risks of nitrous oxide emissions. Journal of Soil and Water Conservation. 67: 137A-144A.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., and Fixen, P. E. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems & Environment. 133: 247-266.

Snyder, C. S., Bruulsema, T. W. and Jensen, T. L. 2007. Greenhouse gas emissions from cropping systems and the influence of fertilizer management—a literature review. International Plant Nutrition Institute, Norcross, Georgia, U.S.A.

Soon, Y. K., Malhi, S. S., Lemke, R. L., Lupwayi, N. Z. and Grant, C. A. 2011. Effect of polymer-coated urea and tillage on the dynamics of available N and nitrous oxide emissions from Gray Luvisols. Nutr. Cycl. Agroecosyst. 90: 267-279.

Statistics Canada. 2014. Agricultural Water Use in Canada: Tables. Table 4.

Statistics Canada. 2013. Agricultural Water Use in Canada 2013. Table 2.

Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T. and Maredia, M. 2013. Green Revolution Research Saved an Estimated 18-27 Million Hectares from Being Brought into Agricultural Production. Proceedings of the National Academy of Sciences. 110: 8363-8368.

Stinson, G., Kurz, W.A., Smyth, C.E., Neilson, E.T., Dymond, C.C., Metsaranta, J.M., Boisvenue, C., Rampley, G.J., Li, Q., White, T.M., Blain, D., 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Glob. Change Biol. 17, 2227-2244.

Tenuta, M. and Beauchamp, E. G. 2003. Nitrous oxide production from granular nitrogen fertilizers applied to a silt loam soil. Can. J. Soil Sci. 83: 521-532.

Tiessen, K. H. D., Flaten, D. N., Bullock, P. R., Burton, D. L., Grant, C. A. and Karamanos, R. E. 2006. Transformation of fall-banded urea: Effect of application date, landscape position, and fertilizer additives. Agron. J. 98: 1460-1470.

Tiessen, K. H. D., Flaten, D. N., Grant, C. A., Karamanos, R. E. and Entz, M. H. 2005. Efficiency of fall-banded urea for spring wheat production in Manitoba: Influence of application date, landscape position and fertilizer additives. Can. J. Soil Sci. 85: 649-666.

Tilman, D., Balzer, C., Hill, J. and Befort, B. L. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences. 108: 20260-20264.

Tuomisto, H. L., Hodge, I. D., Riordan, P., and Macdonald, D. W. 2012. Does organic farming reduce environmental impacts?-A meta-analysis of European research. Journal of environmental management. 112: 309-320.
Ukrainetz, H. 1984. Fertilizer placement for maximum effectiveness. Proc. Alberta Soil Science Workshop, Agriculture Secretary, University of Alberta, Edmonton, AB.

VandenBygaart, A. J., McConkey, B. G., Angers, D. A., Smith, W., de Gooijer, H., Bentham, M. and Martin, T. 2008. Soil carbon change factors for the Canadian agriculture national greenhouse gas inventory. Can. J. Soil Sci. 88: 671-680.

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

Venterea, R. T., Maharjan, B. and Dolan, M.S. 2011. Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. J Environ Qual. 40: 1521-1531.

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 Sci. Soc. Am. J. 74: 407-418.

Vermeulen, S. J., Campbell, B. M. and Ingram, J. S. I. 2012. Climate change and food systems. *Annual Review of Environmental Resources*. 37: 195-222.

Xiaobin, W., Jingfeng, X., Grant, C. A., and Bailey. L. D. 1995. Effects of placement of urea with a urease inhibitor on seedling emergence, N uptake and dry matter yield of wheat. Can. J. Plant Sci. 75: 449452.

Yadvinder-Singh, Malhi, S. S., Nyborg, M. and Beauchamp, E. G. 1994. Large granules, nests or bands: Methods of increasing efficiency of fall-applied urea for small cereal grains in North America. Fert. Res. 38: 61-87.