

USING 4R NUTRIENT MANAGEMENT TO REDUCE N<sub>2</sub>O EMISSIONS AND DETERMINE  
THE AGRI-ENVIRONMENTAL OPTIMUM NITROGEN APPLICATION FOR IRRIGATED  
CANOLA IN SASKATCHEWAN

A Thesis Submitted to the  
College of Graduate and Postdoctoral Studies  
in Partial Fulfillment of the Requirements  
for the Degree of Master of Science  
in the Department of Soil Science  
University of Saskatchewan  
Saskatoon

By

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## ABSTRACT

Saskatchewan has substantial potential to increase the number of irrigated acres in the province which could increase food production. An environmental consideration is the increased greenhouse gas (GHG) emissions often seen from irrigated land compared to dryland cropping. The yield-scaled emission factor (YsEF) can be similar to, or lower than that of dryland systems, however, due to increased yields associated with irrigation. The principles of 4R nutrient stewardship—the Right source, Right rate, Right time, and Right placement of fertilizer—were developed to minimize nutrient losses while still reaching yield targets. In a three-year field plot study, the effects of the 4Rs on GHG emissions were observed. It was found that (i) the highest rates of N fertilizer (165 and 220 kg N ha<sup>-1</sup>) resulted in greater N<sub>2</sub>O emissions; (ii) splitting the fertilizer over two applications instead of one reduced N<sub>2</sub>O emissions, but only at high application rates; and (iii) side-banded N fertilizer resulted in greater emissions in two of three years compared to broadcast and incorporated treatments. Soil moisture and N availability were found to be key factors that influenced N<sub>2</sub>O emissions, with large fluxes occurring after fertilizer applications—especially if closely followed by a precipitation or irrigation event—and small fluxes occurring later in the growing season when the crop would have used the available N. The greatest YsEF was consistently from the side-banded (SB) treatment at a rate of 220 kg N ha<sup>-1</sup>, however in 2015 the broadcast and incorporated (BCI-O) treatment at the same rate had a similarly high value. This research examined potential mitigation opportunities for irrigated canola in the semi-arid prairies and concluded that reducing N rates, splitting fertilizer applications and avoiding side-banding N at high rates may be effective in reducing N<sub>2</sub>O emissions in this area.

## **ACKNOWLEDGEMENTS**

I am very grateful for the support and guidance of my supervisors Drs. Richard Farrell and Reynald Lemke. I would also like to thank my advisory committee, Drs. Jeff Shoenu and Dale Tomasiewicz for their input and assistance.

Financial support that made the study possible was from Saskatchewan Ministry of Agriculture's Agriculture Development Fund, Fertilizer Canada, and the International Plant Nutrition Institute. Personal support was provided by the Department of Soil Science.

Thank you to the 5E19 lab group other staff and summer students, for the technical support and knowledge they shared, and the staff at the Canada-Saskatchewan Irrigation Diversification Centre (CSIDC) for all the hands-on work they provided to make this project happen.

A special thanks to Frank Krijnen and Darin Richman for their endless help and knowledge in the field and in the lab, as well as Mark Cooke, and summer students Justine Larson and Kenzie Derald. Thanks to Dale Tomasiewicz and Don David with Agriculture and Agri-Food Canada for all their assistance setting up and managing the field sites at CSIDC, and finally, to my family and friends for their support and encouragement.

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## LIST OF ABBREVIATIONS

AA	anhydrous ammonia
AFC	automated flux measurement chambers
APP	ammonium polyphosphate
AS	ammonium sulphate
ATS	ammonium thiosulphate
BCI-O	broadcast and incorporated one-time application
BCI-S	broadcast and incorporated split application
CSIDC	Canada-Saskatchewan Irrigation Diversification Centre
ECD	electron capture detector
EF	emission factor
FID	flame ionization detector
FIE	fertilizer induced emissions
FTIR	Fourier transform infrared
GHG	greenhouse gas
GWP	global warming potential
HMR	Hutchinson and Mosier regression
HSD	honestly significant difference
ICDC	Irrigation Crop Diversification Corporation
IPCC	Intergovernmental Panel on Climate Change
IPNI	International Plant Nutrition Institute
LDDA	Lake Diefenbaker Development Area
LWR	long wave radiation

MAP	monoammonium phosphate
PET	potential evapotranspiration
PFRA	Prairie Farm Rehabilitation Administration
PMMA	poly methyl methacrylate
SAFRR	Saskatchewan Agriculture, Food and Rural Revitalization
SB	side-banded
SCC	seed colour change
SIPA	Saskatchewan Irrigation Projects Association
SWR	short wave radiation
TCD	thermal conductivity detector
TSP	triple super phosphate
UAN	urea ammonium nitrate
UHP	ultra high purity
WFPS	water filled pore space
YSeF	yield-scaled emission factor

# 1. INTRODUCTION

## 1.1 General introduction

As the human population continues to increase globally, the amount of food that must be produced also continues to increase. Simultaneously, climate change will impact Canadian agriculture in positive and negative ways. Positive effects may include longer growing seasons and milder winters, but the adverse effects, such as more frequent and prolonged droughts and increased extreme weather events, pose a risk to agricultural production and food security (Agriculture and Agri-Food Canada, 2015). These effects are of concern in semi-arid regions where soil moisture is already the most important factor limiting crop productivity. Irrigation reduces the moisture limitation, resulting in increased and more stable food production.

The province of Saskatchewan is in the center of the Canadian Prairies and the north-central area of the Northern Great Plains ecoregion. The Canadian Prairies, which also includes Manitoba and Alberta, make up the northern part of the Great Plains. This ecoregion is characterized by cold winters, warm summers, strong winds, unpredictable precipitation (300–500 mm per year), and extreme yearly climatic variability (Padbury et al., 2002).

Outlook, Saskatchewan is located approximately 90 km SW of Saskatoon, at the centre of the Lake Diefenbaker Development Area (LDDA), an irrigation area developed to provide a reliable water source to increase and stabilize crop production in the region. This area gets an average of 348 mm of precipitation per year, mainly as rainfall (273 mm) with snowfall averaging



75 mm (water equivalent) per year (Environment Canada, 2015), which provides a vital moisture source for soil during spring melt. Saskatchewan's position relative to the Rocky Mountains and in the centre of the continent leads to a high surface pressure that increases aridity and sunshine hours—over 2000 bright sunshine hours per year in much of the province (Cote, 2006). These factors, combined with strong winds, means potential evapotranspiration (PET) exceeds precipitation and creates a moisture deficit. The moisture deficit for the study area is -250 to -300 mm per year (Agriculture and Agri-Food Canada, 2014). Moisture deficits can be detrimental to crop growth, but irrigation can reduce crop losses from drought conditions (SIPA, 2008a).

Saskatchewan has 46.8% of the total field crop area in Canada, but the type of crops that can be grown is restricted by the lack of soil moisture (SIPA, 2008b). A substantial portion of the acreage in the province may be suitable for irrigation, which could increase production (SIPA, 2008b; Statistics Canada, 2017). Irrigation can stabilize and diversify agricultural production, enabling many crops to be grown that would otherwise be unsuited to dry climates. Irrigated crops are often high value and can contribute significantly to the economy of the region. For example, an estimated 20% of Alberta's total agri-food sector GDP is produced from the less than 5% of cultivated land that is irrigated (Paterson Earth & Water Consulting, 2015; Tollefson and Hogg, 1997). Consequently, there is a clear interest in increasing irrigated acreage in Saskatchewan.

Increasing the irrigated acreage depends on the availability of reliable water supplies and suitable agricultural land, as well as environmental and economic sustainability. Environmental concerns include waterlogging, increased soil salinity, and contamination of groundwater (Tollefson and Hogg, 1997). Since 1997, if the water is from an irrigation district, an Irrigation Certificate is required to develop land for irrigation in Saskatchewan, to ensure that the suitability

criteria are met (Government of Saskatchewan, 2008). Many factors determine the suitability of a soil for irrigation. Certification criteria include soil texture, structure and geological unconformity; infiltration rate, hydraulic conductivity and moisture holding capacity; salinity and sodicity; drainage and depth to water table; landscape; and water quality and availability (Government of Saskatchewan, 2008). This process ensures environmental sustainability and protects water and land resources, as well as the investment in irrigation equipment by the producer. In 2008, the Saskatchewan Irrigation Projects Association (SIPA, 2008) estimated that Saskatchewan has the potential to expand irrigation by over 155,000 hectares in the short term (less than fifteen years) and by more than 725,000 hectares in the long term (more than fifteen years). The area with the highest irrigation potential is the Lake Diefenbaker Development Area (LDDA) located in the Dark Brown Soil Zone—one of several irrigation development areas in Saskatchewan.

Irrigated production is generally more intensively managed than non-irrigated land to ensure high crop yields; this includes the application of higher fertilizer rates and greater inputs of pesticide, fungicide, and herbicide (Mussell et al., 2014). Thus, it is essential to consider the potential adverse environmental impacts, including increased greenhouse gas (GHG) emissions from soils that may result from the more intensive management under irrigation. Greenhouse gases absorb infrared radiation in the atmosphere, which increases the temperature of the Earth's surface. Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) are the most important greenhouse gases associated with agricultural activity. Agricultural soils contribute approximately 80 and 90% of total N<sub>2</sub>O emissions in Canada and Saskatchewan, respectively (Environment Canada, 2016). The global warming potential (100-year time scale) of N<sub>2</sub>O is 298-times that of CO<sub>2</sub> and when transported to the stratosphere N<sub>2</sub>O is destructive to atmospheric ozone and breaks down into NO<sub>x</sub>, a reactive form of nitrogen (Cicerone, 1987; Myhre et al., 2013; Portmann et al., 2012). Nitrous

oxide is produced in soils through the microbially mediated processes of nitrification (aerobic conditions) and denitrification (anaerobic conditions). Many soil factors influence microbial activity, so the interactions of these factors make understanding N<sub>2</sub>O production complex. Nitrous oxide emissions have increased substantially through anthropogenic activities, specifically the increased use of synthetic and organic nitrogen fertilizers in agriculture (Environment Canada, 2016; Hartman et al., 2013). The addition of fertilizers increases the pool of N available in the soil, and when combined with consistent soil moisture from irrigation, there is increased potential for N<sub>2</sub>O production. The principles of 4R nutrient stewardship—Right source, Right rate, Right timing, and Right placement—were developed based on the best management practices for fertilizer use and the goal of the 4R system is to minimize nutrient loss while maintaining yield (IPNI, 2015).

Compared with non-irrigated (rainfed) cropping, irrigated cropping generally results in yield increases. This can result in N<sub>2</sub>O emissions that are similar to or lower than those associated with dryland cropping on a yield-scaled basis (Dobbie et al., 1999). The yield-scaled emission factor refers to the N<sub>2</sub>O emissions per unit of crop yield. Determining fertilizer application practices that will produce the highest crop yield with the lowest yield-scaled emissions will help producers maintain or increase production while limiting negative environmental impacts.

## **1.2 Research objectives**

The primary objective of this study was to identify the agri-environmental optimum application of nitrogen fertilizer for irrigated canola using the principles of 4R nutrient stewardship. The agri-environmental optimum refers to the application strategy and rate of N fertilizer that maintains the agronomic sustainability of high crop yield while limiting the negative

environmental impact from increased N<sub>2</sub>O emissions. This study examined how N<sub>2</sub>O emissions were affected by (i) the application rate of N fertilizer, (ii) the timing of N fertilizer application (i.e., one-time broadcast and incorporated *vs.* split broadcast and incorporated), and (iii) the placement of the N fertilizer (i.e., side-banded *vs.* broadcast and incorporated), with granular urea as the fertilizer source.

### **1.3 Organization of thesis**

This thesis is organized in a traditional format. Following the Introduction, Chapter 2 is a Literature Review that presents a brief history of irrigation in Saskatchewan, greenhouse gas emissions associated with irrigated crop production, and the principles of 4R nutrient management. Chapter 3 outlines the Materials and Methods used during the three years of the study, as well as how the study was set up to determine the impact of the 4R N management practices of rate, placement, and timing of urea fertilizer on N<sub>2</sub>O emissions. Chapter 4 presents the results of the three-year field study, while a discussion of the results is presented in Chapter 5. Chapter 6 gives a summary of the results and the trends of emissions, as well as suggestions for future research. The literature cited is listed in Chapter 7, which is followed by a collection of Appendices that include plot maps (Appendix A), data from the AFC-FTIR system (Appendix B), climate data (Appendix C), contrasts used for ANOVA (Appendix D), soil sampling data (Appendix E), CO<sub>2</sub> data (Appendix F), and the Python scripts (Appendix G).

## **2. LITERATURE REVIEW**

### **2.1 Irrigation history in Saskatchewan**

Irrigation has been practiced in Saskatchewan since before the introduction of the Northwest Irrigation Act of 1894, which defined and provided for the regulation of water rights (Manning, 1988). The federal government gave the provinces authority over water resources in 1930, and the Saskatchewan government put large irrigation systems into place in the southwest region that had been devastated by drought (Manning, 1988). In 1935, the federal government created the Prairie Farm Rehabilitation Administration (PFRA) that was responsible for water supply management and promoted public irrigation projects sponsored by the government (Topham, 1982).

Saskatchewan now contains approximately 8% of the irrigated acres in Canada, and as of 2005, 72% of irrigated land in the province operated under private irrigation licenses as opposed to organized district irrigation (SIPA, 2008b). In Saskatchewan, water for irrigation comes mainly from surface sources; i.e. lakes, rivers, and streams (SIPA, 2008b), and as of 2001 there were 337,600 irrigated acres in the province (SAFRR, 2003). Over half of the irrigated land in Saskatchewan has sprinkler irrigation systems (53%), while the rest is back flooded (28%) or has gravity fed (18%) systems (SAFRR, 2003). Back flood irrigation involves blocking drainage to keep spring runoff in the field long enough to infiltrate and fill the rooting zone, and gravity fed irrigation uses channels to confine water as it flows downslope (SIPA, 2008b). Sprinkler system

technology has been continually improving over the past several decades, and the most common types are wheel-move and centre-pivot systems (SAFRR, 2003). The advantages of sprinkler irrigation are the reduced risk of erosion and salinization and the ability to precisely apply the water required, which increases the water use efficiency (SIPA, 2008b). To conserve irrigation water in Saskatchewan, a common practice is to retain stubble on the field, which is done on 68% of irrigated farms in the province (Statistics Canada, 2016). Crop stubble makes the surface rough which reduces the amount of solar radiation able to reach the soil surface (Horton et al., 1994; Lascano and Baumhardt, 1996). Crop stubble is more reflective because it is a lighter colour than the soil, so the amount of solar radiation that is absorbed is reduced (Horton et al., 1994). Stubble also has a low thermal conductivity, which reduces the heat flux from the soil (Lascano and Baumhardt, 1996). Stubble on the soil surface also improves infiltration into the soil, decreases runoff, and reduces evaporation because the soils are cooler (Government of Alberta, 2001; van Kessel et al., 2013).

The most intensively irrigated region in Saskatchewan is the Lake Diefenbaker Development Area where the Canada-Saskatchewan Irrigation Diversification Centre (CSIDC) is located at the town of Outlook. Irrigation in the area was made possible by the completion of the Gardiner Dam in 1967 and the formation of Lake Diefenbaker (SIPA, 2008b). The LDDA has the potential to expand irrigated acres because there are suitable soils for irrigation, favourable growing conditions and topography, and a consistent water supply (SAFRR, 2003).

### **2.1.1 Irrigated crop management**

Irrigation reduces the soil moisture limitation on crops, which is important during critical growth periods. Reducing this limitation can improve the yield potential and increase the diversity

of crops that can be produced. In Saskatchewan, the most common crop types on cultivated land are cereals, oilseeds, and pulses. Irrigated crops in the LDDA include cereals (47%), forage (26%), pulses (11%), oilseeds (11%), horticultural crops (4%), and herbs and spices (1%) (SAFRR, 2003; Statistics Canada, 2017a). In western Canada, lower value field crops are often grown as rotation crops and a common irrigated cropping rotation may include oilseed, cereal, and pulse crops (ICDC, 2013; Agriculture and Agri-Food Canada, 2016). Choosing a crop rotation is important to maintain and improve soil quality, as well as to reduce pest, disease, and weed pressures. Good crop rotations are flexible enough to allow adjustments if needed, due to climate, soil conditions, crop prices or other issues that may arise (ICDC, 2013; Agriculture and Agri-Food Canada, 2016).

Tillage is a common practice for irrigated land management because it aerates the soil, reduces compaction, reduces disease in the soil, controls weeds, and increases the soil temperature in the spring, which improves seeding conditions (Canola Council of Canada, 2017a; Rothrock, 1992). When used appropriately, tillage can improve the soil, but when done poorly it can lead to soil degradation (Lal, 1991). In Western Canada, reduced tillage practices have been increasingly adopted because of the benefits such as reduced erosion, increased water use efficiency, and reduced field operations, which in turn reduces fuel consumption and cost (Grant et al., 2002; Flynn and Smith, 2010). A disadvantage of this practice is the need for additional chemical inputs to control diseases, pests, and weeds (Grant et al., 2002; Flynn and Smith, 2010). Conservation tillage is a general term for a system that leaves at least 30% of crop residues on the soil surface and encompasses a range of tillage practices including no-till and reduced tillage (Rothrock, 1992; Lal and Kimble, 1997). Reduced tillage practices sequester more carbon in the soil than conventional tillage (Flynn and Smith, 2010), and although the effect on N<sub>2</sub>O emissions is

inconsistent, Marland et al. (2003) found that there is generally a net reduction in GHG emissions through this practice.

The yield potential is higher for irrigated crops because of the reduced moisture limitation, thus recommended rates of fertilizer are higher to meet the increased nutrient requirements of the crop (Grant and Bailey, 1993). For example, the ICDC (2017) recommends 160–180 kg N ha<sup>-1</sup> for irrigated canola in Saskatchewan, compared to 100 kg N ha<sup>-1</sup> recommended for dryland cropping in the dark brown soil zone (Government of Saskatchewan, 2017a). The most common types of nitrogen fertilizers used in Saskatchewan are granular urea (46-0-0), urea ammonium nitrate (UAN) (28-0-0), and anhydrous ammonia (82-0-0) (Government of Saskatchewan, 2017b; Statistics Canada, 2017b).

Irrigated land is often associated with elevated CO<sub>2</sub> and N<sub>2</sub>O emissions compared to dryland cropping due to increased soil water availability, microbial activity, and mineralization of nitrogen (Linn and Doran, 1984; Leibig et al., 2005; Sainju et al., 2012). Irrigated crop production has greater potential for increased GHG emissions because of the intensive management, including increased fertilizer applications, consistent soil moisture, and increased soil disturbance, all of which affect the production of greenhouse gases (Roberts and Chan, 1990; Lemke et al., 1999; Malhi et al., 2006; Sainju et al., 2012). Microbial activity is influenced by soil moisture, so N<sub>2</sub>O production can be stimulated by irrigation (Linn and Doran, 1984; Kessavalou et al., 1998; Liebig et al., 2005). However, Sainju et al. (2012) found that irrigation had only a small effect on GHG emissions and suggested that tillage and N fertilization were the most influential factors.



### **2.1.2 Agronomy of irrigated canola**

The agronomic operations for irrigated canola are very similar to dryland practices, with added requirements such as monitoring soil moisture for irrigation scheduling and checking the crop more frequently for disease, which may be more prevalent because of the increased moisture in the canopy. Additional chemical inputs may be required for this type of cropping system as well as additional fertilizer inputs to target maximum yield.

Two to three years should be scheduled between canola crops in rotation to maintain cropping system diversity and reduce the occurrence of pests and diseases (Canola Council of Canada, 2017a). Canola yield has also been shown to improve when seeding into cereal or pulse stubble (Johnston et al., 2002). Many varieties of canola are grown in Canada and factors like climate, environment, length of growing season, and other local agronomic conditions are taken into consideration when choosing a variety. Most of the canola varieties grown in Canada are hybrids that have been developed to produce higher yields (Canola Council of Canada 2010, 2017a). The seeding date for canola depends on the soil temperature, the weather forecast, and the moisture level in the field; i.e. it must be dry enough to support equipment and allow for proper seed placement (Canola Council of Canada, 2017a). In Western Canada, seeding is recommended to be done in April to early May, though this depends on field conditions so seeding can often occur later. Early seeding can have significant yield benefits but risks damage from spring frost, and there is a higher risk of losses from fall frosts if canola is seeded too late in May or in June. Canola seeds are small and sensitive to deep seeding, so a seeding depth of 12–25 mm is optimal (Canola Council of Canada, 2017a).

Water uptake by canola varies with the growth stage of the plant, ranging from 0.1 mm per day shortly after emergence to 7 mm per day during flowering and pod development (Government of Alberta, 2016). If the soil has sufficient moisture for germination and emergence at seeding, irrigation should be avoided to prevent soil compaction and emergence problems, but if the soil is dry at seeding, frequent light irrigations (15 mm) should be applied to maintain soil moisture and encourage emergence and root growth (Government of Alberta, 2016). During the earliest growth stage, the active root zone is only a few millimetres but will extend to its maximum depth (120–130 cm) at the late flowering stage (Cutforth et al., 2013; Gan et al., 2011; Government of Alberta, 2016). Root distribution is concentrated in the top 50 cm of the soil where the plant acquires most of its water, therefore monitoring water levels in the root zone is important for an effective irrigation strategy (Government of Alberta, 2016). Gan et al. (2011) found that in semi-arid regions, *Brassica* oilseeds were able to produce large volumes of roots when water availability was high, and canola was more sensitive to water availability than wheat. During the flowering stage roots reach their maximum depth, so the monitoring depth of the root zone should be increased to 100 cm; this means larger volumes of irrigation water can be applied less frequently, keeping the canopy drier to discourage the growth of diseases like sclerotinia (Canola Council of Canada, 2017c; Government of Alberta, 2016). An irrigation strategy should include applications of appropriate fungicide to prevent diseases like sclerotinia. If sclerotinia becomes severe, no further irrigation should be applied, but if the crop does not have signs of disease, a final irrigation can be applied in August when the early pods start ripening (Government of Alberta, 2016).

Nitrogen is often the most limiting nutrient for canola, and nutrient uptake increases with time during the early growth stages. Nitrogen uptake reaches the maximum four weeks after emergence, the total N accumulation is greatest nine to ten weeks after emergence (Canola Council

of Canada, 2017a). A mature canola plant contains 0.5–1.5% N, and the seed contains 3.4–4.0% N (Canola Council of Canada, 2017a). Hybrid canola often has a greater yield response to N compared to open pollinated canola, indicating increased N use efficiency (Smith et al., 2010). Wright et al. (1988) found that N response was greater under irrigated conditions for seed yield and total dry matter.

The Canola Council of Canada (2017a) states that swathing, direct combining, or a combination of both can be used to harvest canola, and that seed should reach 60% seed colour change (SCC) before swathing to maximize yield and quality. Green seed is immature and lower quality; the enzymes that clear chlorophyll from the seed require moisture so if the canola is swathed, it should be done on cooler days, so the seed dries at a slower rate. Irrigating the crop can also help to maintain moisture in the seed, and it can then be harvested five to fourteen days later when the moisture content reaches 10%. If direct combining, a shatter-resistant variety should be chosen that can be harvested when pods are dry, and seed moisture has reached 10% or less.

## **2.2 Greenhouse gases from agriculture**

Incoming radiation from the sun arrives as solar shortwave radiation (SWR), mainly from the visible part of the spectrum; about half is absorbed by the Earth's surface, 30% is reflected by gases, clouds, and the Earth's albedo, and around 20% is absorbed in the atmosphere (Cubasch et al., 2013). Incoming solar energy and outgoing radiation must be balanced to keep the temperature on Earth consistent. Outgoing radiation that is emitted from the Earth's surface is longwave, or infrared, radiation (LWR) and is absorbed by water vapour, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and other greenhouse gases, with a significant amount reradiated back to Earth (Cubasch et al., 2013). This is known as the greenhouse effect, and while these gases occur naturally in the atmosphere, anthropogenic

activity has caused the concentration of these gases to increase drastically over a short time, intensifying the greenhouse effect and raising the temperature on Earth. The primary greenhouse gases in the atmosphere are water vapour, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and ozone (O<sub>3</sub>) (Solomon et al., 2007). Agriculture is a significant contributor to anthropogenic greenhouse gas emissions, the most problematic being CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>. Each gas has a different global warming potential (GWP), which is based on how strongly it absorbs energy and how long it stays in the atmosphere (Forster et al., 2007). Global warming potential (100-year time-scale) is stated relative to carbon dioxide, which has a GWP of one; the GWP is 298 for N<sub>2</sub>O, and 25 for CH<sub>4</sub> (Forster et al., 2007). The atmospheric lifetime is how long a gas remains in the atmosphere, which is 5–100 years for CO<sub>2</sub>, 12 years for CH<sub>4</sub>, and 114 years for N<sub>2</sub>O (Forster et al., 2007).

Many agricultural management practices affect greenhouse gas emissions from soils. Field studies on greenhouse gas emissions from irrigated land in the semi-arid prairies have taken place mainly in Alberta, where irrigation is much more prevalent than in Saskatchewan. Other irrigated crop production areas in the Great Plains have been studied and are useful for approximating potential emissions, but the climate and soils of these regions differ, so research must be done locally to accurately quantify emissions (Halvorson and Del Grosso 2013; Mosier et al., 2006; Sainju et al., 2012). Agriculture contributes considerably to global N<sub>2</sub>O emissions, primarily from the use of nitrogen fertilizers. Nitrogen can be released into the atmosphere as several N containing gases, including N<sub>2</sub>, which is not harmful to the environment, as well as gases that have negative environmental impacts like N<sub>2</sub>O, nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) (together referred to as NO<sub>x</sub>), and ammonia (NH<sub>3</sub>) (Robertson and Vitousek, 2009). Nitrous oxide emissions are controlled by many environmental, management, and soil factors, which causes high spatial

variability of emissions within small areas, as well as larger geographic regions (Venterea et al., 2012). This high degree of variability means that N<sub>2</sub>O mitigation practices that are effective at one site may not have the same results at another location.

### **2.2.1 Carbon dioxide**

Carbon dioxide is the most abundant anthropogenic greenhouse gas in the atmosphere and is a natural part of carbon cycling on Earth; however, human activity has led to an increase in atmospheric CO<sub>2</sub> concentration of 100 ppm since the pre-industrial era (Forster et al., 2007). In 2016, CO<sub>2</sub> accounted for 79% of Canada's total greenhouse gas emissions. The main source of CO<sub>2</sub> is burning fossil fuels, and sources from agriculture include land use changes, soil cultivation, and fuel use (Environment and Climate Change Canada, 2018). Carbon dioxide is consumed in large quantities by plant material for use in photosynthesis and is eventually released as CO<sub>2</sub> through respiration or when plants decompose or are consumed (Snyder et al., 2009). In agriculture, soils can be sources or sinks for CO<sub>2</sub> depending on the balance of production and consumption of CO<sub>2</sub>. Carbon dioxide production is predominantly from root respiration and microbial decomposition of soil organic matter (SOM), whereas consumption of CO<sub>2</sub> occurs when it is fixed in plant biomass through photosynthesis and can then be stored as organic C when the plant residue is converted into soil organic matter (Roberts and Chan, 1990; Cole et al., 1997; Grant et al., 2004; Sainju et al., 2008).

Management practices including no-till or reduced-tillage, reducing or eliminating fallow periods, and incorporating C rich residues can increase the amount of carbon stored in the soil, though soils have a finite capacity to sequester carbon (Grant et al., 2004). Tillage enhances decomposition by increasing aeration and microbial activity, leading to increased carbon losses

from the soil as CO<sub>2</sub>, as well as physical losses through soil erosion by wind and water (Lal and Kimble, 1997; Smith et al., 2014). Management changes that may reduce emissions of one GHG may also increase emissions of another, so net emissions must be considered. An example of this is increasing the amount of N fertilizer applied, which would produce more plant material, and thus more material that could be added to the carbon pool in the soil; however, this would likely increase N<sub>2</sub>O emissions, offsetting the benefit of C sequestration (Grant et al., 2004).

### **2.2.2 Methane**

In 2016, methane accounted for 14% of Canada's total emissions and sources included oil and gas, livestock, and landfills (Environment and Climate Change Canada, 2018). In agriculture, the primary sources of methane are livestock and their waste, and flooded soils like rice paddies or wetland areas. Production of methane occurs through methanogenesis, a microbial process that takes place in soils lacking oxygen, where organic matter gets decomposed by methanogenic microbes (Le Mer and Roger, 2001). Methane oxidation is the consumption of CH<sub>4</sub> that occurs under aerobic conditions (Le Mer and Roger, 2001; Oertel et al., 2016). Methane fluxes from agricultural soils are generally small, and soils vary between being small sinks or sources of CH<sub>4</sub>. In the semi-arid prairie region, soils are usually dry and are commonly CH<sub>4</sub> sinks, but the GWP of methane is twenty-five times higher than that of CO<sub>2</sub>, so small fluxes still have a significant environmental impact (Liebig et al., 2005; Mosier et al., 2006. Forster et al., 2007).

### **2.2.3 Nitrous oxide**

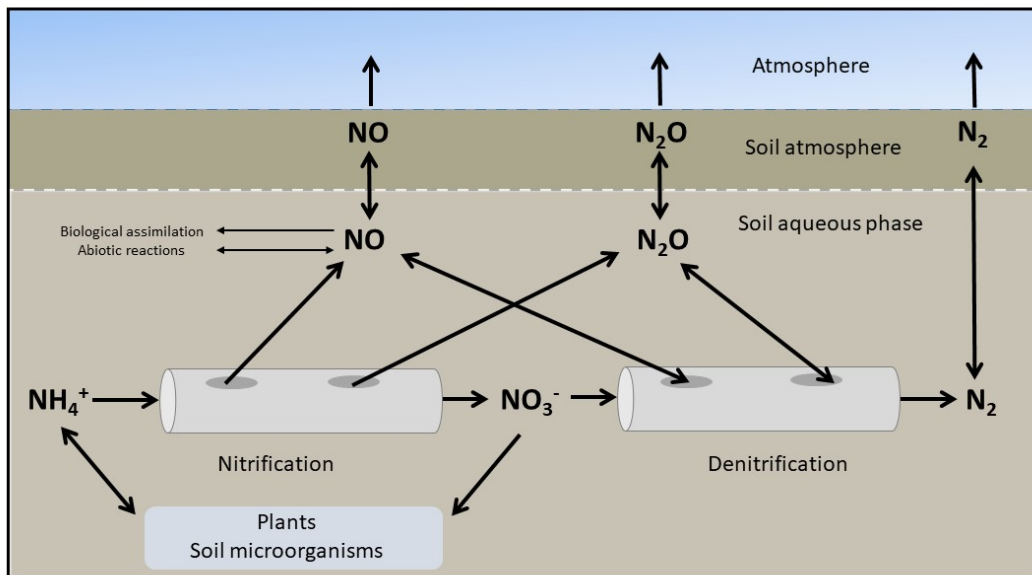
In 2016, N<sub>2</sub>O accounted for 5% of Canada's total GHG emissions and 77% of N<sub>2</sub>O was generated by agriculture (Environment and Climate Change Canada, 2018). Globally, approximately 40% of atmospheric N<sub>2</sub>O is of anthropogenic origin (Solomon et al., 2007).

Agricultural activities change the scale and pattern of the N cycle, which can increase N<sub>2</sub>O emissions (Hutchinson et al., 2007). Nitrous oxide is the main non-CO<sub>2</sub> greenhouse gas emitted from soils, and agriculture is the dominant source of anthropogenic N<sub>2</sub>O worldwide (Mosier et al., 2006).

Plant available nitrogen is often lacking in soils; this limits plant growth because it is an essential element for growth. There is no source of N that can be released through the weathering process of rocks from which the soil is derived, unlike other essential nutrients like phosphorus, calcium, and potassium (Robertson and Vitousek, 2009). Therefore, N must come from outside sources, especially while cropping intensity has increased over the last century (Robertson and Vitousek, 2009). The discovery of the Haber-Bosch process in the early 20<sup>th</sup> century led to commercial production of N fertilizer, which is now the primary source of reactive N; it is mobile, difficult to contain in the environment, and can have negative impacts on downwind and downstream ecosystems (Robertson and Vitousek, 2009). Agricultural land has increased emissions of N<sub>2</sub>O due to the increased N availability from applied fertilizers, biological N fixation from leguminous crops, and N deposition (Ehhalt et al., 2001).

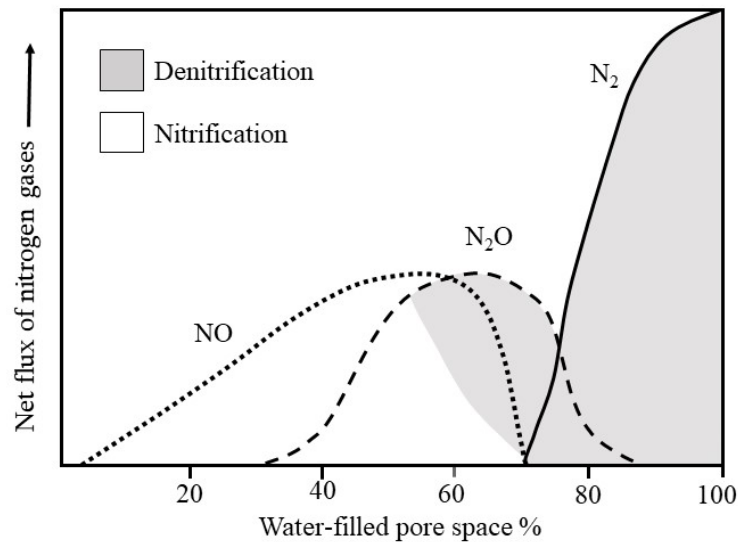
Production of N<sub>2</sub>O occurs through nitrification and denitrification by microbes in the soil. Nitrification is the process by which nitrifying bacteria convert ammonium (NH<sub>4</sub><sup>+</sup>) to nitrite (NO<sub>2</sub><sup>-</sup>) and nitrate (NO<sub>3</sub><sup>-</sup>) under aerobic conditions (Fig. 2.1). Denitrification is the process where nitrate is reduced to nitrite (NO<sub>2</sub><sup>-</sup>), nitric oxide (NO), N<sub>2</sub>O, and nitrogen gas (N<sub>2</sub>) under anaerobic conditions (Fig. 2.1), such as when water-filled pore space (WFPS) is above 60% (Fig. 2.2) (IPNI, 2016). If the denitrification pathway is completed, N<sub>2</sub> is released back to the atmosphere, which does not have a negative impact on the environment. If the pathway is not completed however,

nitrogen is released as  $N_2O$  and  $NO_x$ , which has serious implications for global emissions (Robertson and Vitousek, 2009). Nitrous oxide emissions are influenced by the available N, soil water content, and soil temperature, which results in the emission potential being highly variable both spatially and temporally (IPNI, 2015). Emissions often occur as short-lived peaks in certain areas or time periods when conditions are ideal (Halvorson et al., 2008). Denitrification will increase with higher soil moisture when anaerobic conditions prevail and reduction of  $NO_3^-$  is favoured by denitrifying organisms (Nyborg et al., 1997; Burton et al., 2008a). When nitrogen fertilizer is applied in an amount that exceeds plant nutrient requirements, the potential for  $N_2O$  emissions is high. Along with the appropriate rate of fertilizer, the placement and timing of fertilizer applications can affect the  $N_2O$  losses from the soil over the growing period (IPNI, 2015).



**Figure 2.1.** “Hole-in-the-pipe model” that shows the pathways of  $N_2O$  production and emission from soils. This model shows the factors that influence rates of nitrification and denitrification (the amount of N flowing through the pipe), the factors that affect the gases produced (size of holes in the pipe), and the factors that affect the diffusion of gases through the soil and atmosphere. (Adapted from Firestone and Davidson, 1989 and Davidson et al., 2000).





**Figure 2.2.** A model representing the relationship between water-filled pore space in the soil and the type and magnitude of nitrogen gases emitted. In this model, peak  $N_2O$  emissions occur between 60-70% WFPS (Adapted from Davidson, 1991).

Soil moisture is a significant factor controlling  $N_2O$  emissions because it affects the availability of oxygen to soil microbes (Butterbach-Bahl, 2015). High emissions of  $N_2O$  are often associated with high soil water content, such as during snowmelt, after irrigation or rainfall, and especially after wetting a dry soil (Davidson, 1991; Rudaz et al., 1991; Lemke et al., 1999). Spring thaw is generally a period of high emissions, representing up to 70% of annual  $N_2O$  emissions in some studies (Nyborg et al., 1997; Lemke et al., 1998; Liebig et al., 2005). Researchers have speculated that this is due to chemical reactions with nitrate, biological processes, or  $N_2O$  accumulation in frozen subsoil that is released when thawed (Müller et al., 2002). Nyborg et al. (1997) reported that emissions were caused when a saturated soil zone at the surface developed due to the lack of drainage when the lower layers of soil are still frozen. A study by Röver et al. (1998) found that sterilized soil did not produce  $N_2O$  emissions during freeze-thaw periods,

concluding that this high emission period is due to biological activity. Many fungi and bacteria die during freezing, and the leaked intracellular material becomes available as nutrients for the microbes that remain, causing bursts of activity during warming (Müller et al., 2002). During the growing season in the northern great plains, N<sub>2</sub>O emissions generally follow a pattern of large fluxes following fertilization and rainfall or irrigation events while N supply exceeds crop demand (i.e., 30 to 40 days after planting), and then declining in the latter part of the growing season as the N availability is reduced due to crop growth (Halvorson et al., 2008; Hao et al., 2001).

### **2.3 4R Nutrient Stewardship**

The principles of 4R nutrient stewardship were developed from best management practices (BMPs) to increase production and profitability for farmers while improving environmental sustainability (IPNI, 2015). The concept is to apply the Right fertilizer source at the Right rate and Right time, with the Right placement to match the supply of nutrients with the needs of the crop to minimize losses and optimize fertilizer efficiency (IPNI, 2015). Whereas 4Rs principles always remain the same, how they are adapted locally is based on soil, climate, crop, and social and economic conditions (IPNI, 2015). The 4Rs are interconnected, and successful nutrient management must integrate each principle to achieve an optimal agricultural outcome while limiting the environmental impact, which is referred to as the agri-environmental optimum in this thesis. For example, applying the Right source and Right rate of N fertilizer at a time that does not coincide with crop demand may result in very high gaseous losses from the soil. How efficiently plants use N is controlled by several factors: crop type, climate (temperature, precipitation), soil characteristics (texture, organic matter content, compaction, pH, CEC), agronomic practices

(tillage, crop rotation, pest management), and fertilizer application (Malhi et al., 2001). To optimize N management, each of the 4Rs must be considered.

### **2.3.1 Nitrogen rate and emissions**

One of the only widely recognized ways of reducing N<sub>2</sub>O emissions is to reduce the rate of nitrogen applied, especially if the rate of N applied exceeds the requirements of the crop (Chantigny et al., 1998; Grant et al., 2006; McSwiney and Robertson, 2005; Roy et al., 2014). There is no single optimum rate of nitrogen fertilizer as it is dependent on many factors, including crop type and cultivar, soil fertility, water availability, and pest, disease, and weed pressures (Metwally et al., 2011). A general yield response curve to nitrogen fertilizer is nonlinear and generally follows a continuous diminishing returns response, where the yield response progressively decreases as the fertilizer rate increases (Colwell, 1994; Kachanoski, 2009; Schlegel et al., 2005; Metwally et al., 2011). Reducing the amount of N applied is a potential risk to yield and profit, so it may not be readily adopted by producers (Venterea et al., 2012).

The amount of N a producer would be willing to reduce depends on the risk of production uncertainty they are inclined to accept; risk-averse producers would be more likely to over-apply N to minimize the potential impact on yield from uncontrollable factors, such as weather (Babcock, 1992). Crop yield and optimal N rate are highly dependent on climatic conditions, as the rate recommended for favourable conditions may be an over-application if the growing conditions are unfavourable and yields will naturally be lower (Venterea et al., 2012; Babcock, 1992). Chantigny et al. (1998) found that increasing fertilizer rates led to higher N<sub>2</sub>O emissions and suggested that N<sub>2</sub>O production is more dependent on the amount of unused N in the soil rather than the total amount applied. Liebig et al. (2005) averaged the results of five studies from northwestern USA

and western Canada that applied several N rates and found that N<sub>2</sub>O emissions increased significantly with every 100 kg N ha<sup>-1</sup> that was applied. In contrast to these studies, Zebarth et al. (2008) found that fertilizer rate did not influence cumulative N<sub>2</sub>O emissions from corn in Atlantic Canada over a two-year study. These results highlight the variability of N<sub>2</sub>O by region and the need to tailor recommendations to local, or at least regional, conditions.

### **2.3.3 Nitrogen timing and emissions**

In cropping systems, one of the greatest contributors to N loss is when the timing of N availability and crop need do not match. Ideally, N would be applied multiple times over the growing season to correspond with periods when plant demand is high (Robertson and Vitousek, 2009). Logistically that may not always be practical for producers, thus BMPs recommend applying nitrogen close to when the crop would require it, such as at seeding and during the plant's rapid growth phase several weeks later (Robertson and Vitousek, 2009; Ribaudo et al., 2011). A large proportion of N<sub>2</sub>O emissions occur as large pulses after events like spring thaw, irrigation or rainfall, and fertilizer application (Burton et al., 2008a). Applying N fertilizer when crop uptake is high can reduce denitrification, and therefore N<sub>2</sub>O emissions, by reducing the amount of time nitrate (NO<sub>3</sub>) is highly concentrated in soil (Zebarth et al., 2008). Splitting the N fertilizer into several applications instead of a single application can reduce emissions by decreasing the N available in the soil when conditions are favourable for N<sub>2</sub>O production. Whether or not splitting the fertilizer application is effective in reducing N<sub>2</sub>O emissions is not certain because a limited number of studies have been done and have shown inconsistent results (Venterea and Coulter, 2015). A study by Burton et al. (2008b) with potatoes, showed reduced N<sub>2</sub>O emissions from splitting N fertilizer in one of two study years, but only when environmental conditions favoured

denitrification. Zebarth et al. (2012) found that a split application did not significantly reduce N<sub>2</sub>O emissions compared to the single conventional application in a potato cropping system. Allen et al. (2010) found that with a sugarcane crop, splitting the N application did not reduce N<sub>2</sub>O emissions at the total N rate of 100 kg N ha<sup>-1</sup>, however emissions were significantly reduced when the total N rate was 200 kg N ha<sup>-1</sup>. Under some conditions, it is possible that splitting the fertilizer application can increase N<sub>2</sub>O emissions. Venterea and Coulter (2015) found that the cumulative emissions from the split fertilizer application were higher than the single application. They hypothesized that this was due to a lack of rainfall around the time of the split fertilizer applications that inhibited the movement of N and limited the uptake from the crop. Thus, when large rainfall events occurred, the high levels of N in the soil created conditions conducive to large and prolonged N<sub>2</sub>O fluxes. The mixed results from these studies highlight the complexity of N<sub>2</sub>O production that makes managing emissions difficult.

### **2.3.2 Nitrogen placement and emissions**

Studies examining the effect of fertilizer placement on N<sub>2</sub>O emissions also have shown inconsistent results, with soil type and climate factors playing a substantial role. Some studies have shown that banding fertilizer may be more beneficial than broadcasting because the contact between the fertilizer and soil microorganisms is reduced, which decreases immobilization of ammonium (NH<sub>4</sub>) and nitrate (NO<sub>3</sub>) (Malhi et al., 2001). Placing the fertilizer in a band also slows the conversion of urea to ammonia (NH<sub>3</sub>) and NH<sub>4</sub> to NO<sub>3</sub>, which are susceptible to leaching and denitrification (Malhi et al., 2001; Engel et al., 2010). Alternatively, Yan et al. (2001) found that banded fertilizer applications had lower emissions than surface applied urea for the first two weeks, but emissions increased afterwards, resulting in total emissions that were nearly the same for both

treatments. The banded treatment had a lower N rate applied and the researchers stated the results indicated that banded fertilizer could provide mineral N for N<sub>2</sub>O emissions longer than broadcast, concluding that banding was not an effective strategy for reducing N<sub>2</sub>O emissions.

Surface broadcast urea can be susceptible to ammonia volatilization because it sits on the surface until precipitation moves it into the soil, however incorporating it below the surface drastically reduces volatilization losses (Malhi et al., 2001). A study by Burton et al. (2008a) found no significant difference in cumulative emissions between spring broadcast and banded applications over three years at two sites in Manitoba. Engel et al. (2010) found banded N applications had higher cumulative emissions than broadcast applications in one year, but the following year the emissions were not different between placements. High soil moisture may have diluted the N in the band in the year that they reported no difference. Hultgreen and Leduc (2003) reported higher N<sub>2</sub>O emissions from broadcast urea than the banded application in two out of three years at two out of four Saskatchewan sites, with no significant difference in emissions at the two other sites, noting the challenging weather conditions encountered over the course of the study as likely the reason for the inconsistent results. As seen from these studies, placement of N fertilizers varies in effectiveness as a way of reducing N<sub>2</sub>O emissions.

#### **2.3.4 Nitrogen source and emissions**

Nitrogen sources used in crop production can be organic or inorganic. Organic N sources include animal manures and green manures. Green manuring is when a crop is grown to be incorporated into the soil to provide N for the subsequent crop. Generally, this is done with legumes because they biologically fix N from the atmosphere. Animal manures are an important nutrient source, but manure management must be carefully considered; the available N is often

low and variable, and continuous application of manures can cause a buildup of phosphorus (P) in the soil that can end up in aquatic systems through surface runoff, negatively impacting water quality (Government of Manitoba, 2009; Government of Saskatchewan, 2017b). Sources of inorganic nitrogen are available in gaseous, liquid, and granular forms. The most commonly used nitrogen fertilizers in Saskatchewan are granular urea (46-0-0), liquid urea ammonium nitrate (UAN) (28-0-0), and gaseous anhydrous ammonia (82-0-0) (Government of Saskatchewan, 2017b; Statistics Canada, 2017b). Other common fertilizers that contain N in addition to other nutrients include ammonium sulphate (AS) (20-0-0-24), mono-ammonium phosphate (MAP) (11-52-0), ammonium polyphosphate (APP) (10-34-0) and ammonium thiosulphate (ATS) (15-0-0-20) (Government of Saskatchewan, 2017b). Several types of enhanced efficiency fertilizers (EEFs) are also available, such as coated granular products that slow the release of N, or fertilizers that contain nitrification or urease inhibitors that slow the conversion of urea to ammonia or ammonium to nitrate, which may result in reduced N<sub>2</sub>O emissions under some conditions (Akiyama et al., 2010). Fertilizer sources must be carefully considered to ensure the crop's nutrient requirements are met, and the environmental impact is minimized.

## **2.4 Emission Factors**

Total N<sub>2</sub>O emissions are not a reliable way to compare emissions between years or between studies because emissions are highly influenced by local climate and soil factors. Emission factors allow for more reliable comparisons, and in this study the fertilizer induced emissions (FIE), emission factor (EF), and yield-scaled emission factor (YsEF) were calculated. Emissions from the check plots (0 N) represent background emissions that occur naturally from soil, so the difference between background emissions and those from the N fertilized treatments defines the

fertilizer induced emissions (FIE) (Hultgreen and Leduc, 2003), i.e., the total cumulative emissions derived from the fertilizer.

$$FIE = E_N - E_C \quad (\text{Eq. 2.1})$$

where  $E_N$  = cumulative  $N_2O$  emissions from the fertilized plots ( $g N_2O-N ha^{-1}$ ) and  $E_C$  = cumulative  $N_2O$  emissions from the check plots ( $g N_2O-N ha^{-1}$ ). The FIE is a value of the emissions that are caused by fertilizer but does not take the rate of fertilizer into consideration. The emission factor (EF) does, and it represents the percentage of the applied fertilizer N that has been lost as  $N_2O$  (Gao et al., 2017) and is calculated by the equation:

$$EF = \frac{FIE}{TN} \times 100 \quad (\text{Eq. 2.2})$$

where  $TN$  = the total N applied ( $kg N ha^{-1}$ ). The yield-scaled emission factor (YsEF) represents the amount of  $N_2O$  emissions caused by applied N fertilizer and is analogous to GHG intensity (Johnson et al., 2012). The equation used to calculate the yield-scaled emission factor (YsEF) is:

$$YsEF = \frac{E_N}{Y} \quad (\text{Eq. 2.3})$$

where YsEF represents the  $N_2O$  emissions produced per unit of yield;  $E_N$  = cumulative  $N_2O$  emissions ( $g N_2O-N ha^{-1}$ ); and  $Y$  = seed yield ( $kg ha^{-1}$ ) (van Groenigen et al., 2010). Higher fertilizer rates generally have higher  $N_2O$  emissions but also higher yields, so the emissions from higher N rates can be similar to lower rates on a per unit of yield basis. The YsEF also allows for the comparison of  $N_2O$  emissions between different crop types. High yields are necessary to ensure food will be available for the growing population without having to increase the amount of land used for cropping, and an optimized system would produce high yields while limiting excess fertilizer in the soil, resulting in lower GHG emissions.



### 3. METHODS AND MATERIALS

#### 3.1 Experimental design

The study sites were located at the Canada-Saskatchewan Irrigation Diversification Centre at Outlook, SK (51° 28' 31" N, 107° 3' 9" W) on a dominantly calcareous Bradwell sandy loam soil that is non-saline. The pH was high at ~8, and the soil organic carbon ranged from 1.2–1.5% at 0–15 cm for the three fields in the study. The plots were set up in a randomized complete block design (RCBD) with nine treatments replicated once in each of the four blocks. Individual plots were 3.048 m wide by 10–11 m long. The study site was moved to a different location each year to seed the canola (*Brassica napus L.*) after unfertilized wheat (*Triticum aestivum L.*) to avoid confounding effects from the previous crop and residual nitrogen fertilizer. Bulk soil samples were taken in the spring to determine the existing soil nitrogen levels. The fertilizer applications included: i) N rates of 0, 55, 110, 165, and 220 kg N ha<sup>-1</sup>, ii) N timing (one-time broadcast and incorporated [BCI-O] vs. split broadcast and incorporated [BCI-S]) at 110 and 220 kg N ha<sup>-1</sup>, and iii) N placement (broadcast and incorporated [BCI-O] vs. side-banded [SB]) at 110 and 220 kg N ha<sup>-1</sup> (Table 3.1).<sup>1</sup> All N was applied as urea (46-0-0). For the split application (BCI-S), half of the urea was applied just before seeding and incorporated, and the other half was applied as a top dress before bolting, followed by irrigation to move the fertilizer into the soil. Irrigation was supplied

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<sup>1</sup> This research was a continuation and expansion of a project established by Dr. D. Tomaszewicz at CSIDC examining the fertilizer rate, timing, and placement and followed the protocols established by him.

based on soil moisture measured by three (2014) or four (2015 and 2016) pairs of WATERMARK soil moisture sensors (Irrometer Company Inc., Riverside, CA) at 25-cm and 75-cm depths.

**Table 3.1. Nitrogen fertilizer application strategy and rates.**

Application	----- N Rate (kg ha <sup>-1</sup> ) -----			
Check	0			
BCI-S	55	110	165	220
BCI-O	110		220	
SB	110		220	

### 3.1.1 Field operations

In 2014, the study was located in CSIDC Field #6 and covered an area 30.48-m wide by 51-m long with no gaps between or within plots (Fig. A.1). The area was pre-worked twice with a Res-Till cultivator (10 cm depth) on May 8 to speed up the drying process. The soil was sampled on May 12, and Edge Granular herbicide was broadcast at 17 kg ha<sup>-1</sup> and incorporated. On May 14, a blanket broadcast application of triple superphosphate (TSP 0-45-0) at 60 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> and potassium sulphate (K<sub>2</sub>SO<sub>4</sub> 0-0-50-17) at 36 kg K<sub>2</sub>O ha<sup>-1</sup> and 12 kg S ha<sup>-1</sup> took place. Urea (46-0-0) was applied to the one-time broadcast and incorporated (BCI-O) and split broadcast and incorporated (BCI-S) treatments and incorporated with the Res-Till cultivator (approximate depth 7.6 cm), followed by harrow-packer. Tillage for fertilizer incorporation was conducted over the entire study area. Seeding was done with a double disc plot drill with 25.4 cm row spacing, 1.2 cm deep at 7.5 kg ha<sup>-1</sup>, which was the same for each year of the study. Side-banded (SB) N was applied during seeding by banding urea 2.5 cm to the side of and 5 cm below the seed row. The canola stand did not establish well due to heavy rain that washed soil into the seed rows shortly after

seeding and may have compacted the soil enough to affect emergence. A second seeding was done on June 3, followed by a third on June 16 that resulted in a better stand. For the third seeding operation, the drill was operated across the plots instead of down the length of them. The GHG chambers were not removed, so the area around them (approximately 2.5 m at the end of each plot) was seeded by hand broadcasting and raking in the seed. There was no additional N added during the second and third seeding operations. The method used for the top dress urea application was the same in all study years—top dress urea for the BCI-S treatments was applied and followed with light irrigation (8 mm). The gas sampling chambers were covered during the top dress application and fertilizer that fell on the lid was discarded. The fertilizer inside the chambers was applied separately—urea was weighed and then applied inside each chamber to ensure the N rate was accurate. The study area was sprayed with a herbicide mix of Liberty 150SN (3.34 L ha<sup>-1</sup>) and Arrow (0.37 L ha<sup>-1</sup>), Lance WDG fungicide (350 g ha<sup>-1</sup>), and Decis insecticide (0.1 L ha<sup>-1</sup>) (Table 3.2).

In 2015, the study was moved to Field #12 where space constraints required a minor adjustment to the plot layout (Fig. A.2). Field operations were the same as reported for the 2014 field season, with the following changes: the field site was pre-worked once with a Res-Till cultivator, and TSP (0-45-0) was applied to all plots at a rate equivalent to 80 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup>. Pesticides used in the 2015 field season included Liberty 150SN herbicide (3.34 L ha<sup>-1</sup>), Lance WDG fungicide (350 g ha<sup>-1</sup>), and Decis insecticide (0.15 L ha<sup>-1</sup>). Refer to Table 3.2 for a summary of the field operations.

**Table 3.2. Site management information for each year of the study at the CSIDC, Outlook, SK.**

	2014		2015		2016	
<b>Location</b>	Field # 6 SW15-29-8-W3		Field # 12 SE15-29-8-W3		Field # 6 SW15-29-8-W3	
	<b>Management</b>					
<b>Seeding</b>		- date -		- date -		- date -
Crop	Canola	May 14 Jun 03 Jun 16	Canola	May 12	Canola	May 18
Variety	<i>InVigor L252</i> <sup>†</sup>		<i>InVigor L252</i>		<i>InVigor L252</i>	
<b>Swathing</b>		Sep 22		Aug 21		Aug 26
<b>Harvest Yield</b> (kg ha <sup>-1</sup> ) <sup>‡</sup>	2268	Oct 08	3611	Sep 21	3729	Sep 08
	<b>Crop inputs</b>					
<b>Fertilizer</b>		- date -		- date -		- date -
TSP <sup>¶</sup>		May 14		May 12		May 18
Urea		May 14		May 12		May 18
Top dress <sup>§</sup>		Jul 17		Jun 23		Jun 21
<b>Chemical</b>						
Herbicide <sup>#</sup>	<i>Edge Granular</i>	May 12	<i>Edge Granular</i>	May 01		
	<i>Liberty 150SN Arrow</i>	Jul 20	<i>Liberty 150SN</i>	Jun 15	<i>Liberty 150SN Centurion</i>	Jun 08
Fungicide <sup>††</sup>	<i>Lance WDG</i>	Aug 04	<i>Lance WDG</i>	Jul 06	<i>Lance WDG</i>	Jul 04
Insecticide <sup>‡‡</sup>	<i>Decis</i>	Aug 21	<i>Decis</i>	Jul 08		

<sup>†</sup> Hybrid canola (*Brassica napus*); Bayer CropScience Canada.

<sup>‡</sup> Average yield for all fertilizer treatments; does not include check (0N) plots.

<sup>§</sup> Top dress for the split broadcast fertilizer applications only.

<sup>¶</sup> Triple Superphosphate. In 2014 only, K<sub>2</sub>SO<sub>4</sub> was added with TSP equivalent to 36 kg K<sub>2</sub>O ha<sup>-1</sup> and 12 kg S ha<sup>-1</sup>.

<sup>#</sup> Edge Granular (Dow AgroSciences; AI = ethalfluralin); Liberty 150SN (Bayer CropScience Canada; AI = glufosinate ammonium); Arrow (Adama Canada; AI = clethodim); Centurion (Bayer CropScience Canada; AI = clethodim - Group 1)

<sup>††</sup> Boscalid (BASF Canada)

<sup>‡‡</sup> Deltamethrin (Bayer CropScience Canada)

In 2016, the study was relocated to an area east of the original 2014 site in Field #6, and with the same plot layout. On May 18, a blanket application of TSP (0-45-0) at 50 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> was applied to all plots. Urea (46-0-0) was also applied to the BCI-S and BCI-O treatments with a plot drill, incorporated with a cultivator at cross directions (~7.6 cm deep), followed by harrow packer. The side-banding was done at the time of seeding, banding urea 3 cm to the side and 4 cm below the seed row. The study area was sprayed with a herbicide mix of Liberty 150SN (3.34 L ha<sup>-1</sup>) and Centurion (0.06 L ha<sup>-1</sup>), and Lance WDG fungicide (346 g ha<sup>-1</sup>) (Table 3.2). 3.2 Soil emission measurements

### 3.2.1 Manual sampling

Greenhouse gas fluxes from all treatments were measured using square 25.4 × 25.4 × 15 cm vented, non-flow through, non-steady state chambers made from 6 mm thick clear poly-methyl methacrylate (PMMA, “acrylic”) (Fig. 3.1B). After seeding, a GHG chamber base was installed 5 cm into the soil in each plot (n = 35), yielding a headspace volume of 6.45 L over an area of 645 cm<sup>2</sup>. The chambers were placed between the seed rows and included the fertilizer band, where there was one, and remained in place throughout the growing season. Canola was hand seeded along the outside of the two sides of the chamber that were parallel to the seed row, thus ensuring that the plant density beside the chambers was similar to the rest of the plot. The bases were left in the ground over winter to allow for measurements the following spring when the ground would still be frozen and re-installation would be too difficult.

When the plots were sampled, the bases were covered with an insulated PMMA lid, which allowed the gases to accumulate; gas samples were then collected at a single time point (20 min) after the chamber lid was placed on the base. To obtain the gas sample, a 20-mL disposable syringe

fitted with a 22-gauge needle was inserted through a rubber septum in the lid with. The sample was then drawn into the syringe, injected into pre-evacuated 12-mL Exetainer® vials (Labco Limited, UK), and transported to Saskatoon for analysis at the University of Saskatchewan's Prairie Environmental Agronomy Research Laboratory (PEARL). Four ambient air samples were also taken to represent time zero. Manual sampling was conducted 2–3 times weekly when emission potentials were high (i.e. during spring thaw, after fertilizer applications, and after irrigation or high rainfall events), and less frequently during the remainder of the growing season until the soil froze.



**Figure 3.1.** Photo showing (A) the AFC-FTIR automated gas sampling chamber and (B) the MFC-GC manual gas sampling chamber in the field.

Potential issues related to the closed chamber method used in this study were described by Mosier (1989) and included: i) high concentrations of gas potentially inhibiting normal emissions from the soil, ii) atmospheric pressure being altered at the soil surface, iii) pressure changes in the soil when the chamber is inserted, and iv) temperature and humidity differences between the chamber and outside atmosphere. To mitigate these issues, the sampling period was shortened (20 min) so that gas buildup was limited; the lids were equipped with a vent tube to allow the pressure to be equalized while minimizing mixing with outside air; the bases were installed at seeding and left open except during sampling periods to minimize soil disturbance; and the lids had a reflective insulation to limit heating inside the chamber.

Concentrations of CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub> were measured using gas chromatography (GC) (Farrell and Elliot, 2008). The GC (Bruker 450 GC, Bruker Biosciences Corporation, MA, USA) was equipped with three detectors: a thermal conductivity detector (TCD) for determining CO<sub>2</sub>, a flame ionization detector (FID) for determining CH<sub>4</sub>, and a <sup>63</sup>Ni electron capture detector (ECD) for determining N<sub>2</sub>O. The GC was fitted with a CombiPAL autosampler (CTC Analytics AG, Zwingen, Switzerland) that injected 2 mL of sample into the GC where it passed through two 500 µL sample loops that injected the sample onto the two columns. The sample passed through a HayeSep N, 80/100 column (0.5 m × 3.18 mm), followed by a Porapak QS, 80/100 column (1 m × 3.18 mm) to reach the TCD and FID. These detectors operated at 120°C (filament at 250°C) and 300°C respectively, with UHP He as the carrier gas. The second sample loop injected the sample onto a HayeSep N, 80/100 column (0.5 m × 3.18 mm), followed by a HayeSep D, 80/100 column (2 m × 3.18 mm) to reach the ECD. This detector operated at 370°C and used Ar:CH<sub>4</sub> (95:5 ratio) as the carrier gas. The injector, valves, and columns were maintained at 70°C, with a runtime of three minutes. Daily fluxes were determined using a linear regression. The daily fluxes reported

are the mean daily flux of each treatment from the four replicate plots, one per block. Cumulative fluxes were calculated by linear interpolation using an area-under-the-curve (AUC) analysis of the daily flux vs. time plot (David et al., 2018).

Each N<sub>2</sub>O production year (PY) began at seeding/fertilizer application in the spring and included the growing season of that year and early spring of the following year (including the thaw period), ending before seeding/fertilizer application of the plots for the next year. Production years will subsequently be referred to as PY1 (growing season of 2014 and spring of 2015), PY2 (growing season of 2015 and spring of 2016) and PY3 (growing season of 2016 and spring of 2017). There was a gap in sampling in PY3 after harvest when the lab was short of personnel to get to the field to sample. The next time sampling occurred, emissions were higher than expected, so extrapolating with this point led to an overestimation of the cumulative emissions. Thus, the period over which there was no sampling is not included in the cumulative emission calculation, which likely means emissions are slightly underestimated; however, emissions are assumed to be very low at this point in the year. The manual sampling chamber frames were left in the ground over the winter to make sampling possible during the spring, however, no gas samples were taken over the winter months. Nitrous oxide emissions in this region are considered insignificant when the soil is frozen, snow-covered, and temperatures are very low and stable (Dörsch et al., 2004; Malhi et al., 2001). With the constant low temperatures, the soil does not undergo freeze-thaw activity, which is thought to be the cause of high N<sub>2</sub>O fluxes during the winter (Rochette et al., 2008a; Wagner-Riddle and Thurtell, 1998).

Nitrous oxide emissions from the check plots represent background emissions, and the fertilizer-induced emissions (FIE) were defined as the difference in cumulative N<sub>2</sub>O emissions



between the check and N fertilizer treatments, calculated from Equation 1. The emission factor (EF) represents the percentage of the applied fertilizer N lost as N<sub>2</sub>O and was calculated from Equation 2, and the yield-scaled emission factor (YsEF) was calculated from Equation 3 (Section 2.4).

The literature is not consistent when reporting FIE and EF, and their definitions are sometimes different than stated here. When comparing values in the literature to this study, the terms defined here will be compared to the equivalent term in the literature. For all these measures, the higher the value, the greater are the emissions associated with a given treatment.

### **3.2.2 Automated sampling**

In addition to the single time point manual sampling method, an automated system was used to monitor fluxes several times per day. The AFC-FTIR system developed at the University of Saskatchewan (U of S) consists of a Fourier Transform Infrared (FTIR) gas analyzer (Model DX-4015, Gaset Technologies Oy, Helsinki, Finland) and multiplexer (LI-8150, Li-Cor Biosciences, Lincoln, NB) interfaced to a series of automated flux measurement chambers (AFC) (LI-8100-104, Li-Cor Biosciences, Lincoln, NB). Two FTIR systems were deployed, each interfaced to ten chambers in 2014, that measured the check (0 N) and BCI-S treatments (55, 110, 165, 220 kg N ha<sup>-1</sup>). The FTIR systems were expanded to fourteen chambers in 2015 and 2016, which allowed for multiple measurements per day in the SB (110 and 220 kg N ha<sup>-1</sup>) plots as well. The chambers were placed between seed rows and included a fertilizer band where there was one (Fig. 3.1A). Each chamber was sampled over a fifteen-minute period six to seven times per day, which resulted in high temporal resolution of daily and seasonal GHG flux estimates. Two trailers were set up in the field, each housing an FTIR, multiplexer, and computer. One AFC-FTIR system

was set up between Blocks I and II, and the second in Blocks III and IV. Each FTIR system sampled one chamber at a time: when the chamber lid closed, the gas concentration was continuously measured by the FTIR for fifteen minutes, after which, the lid opened, and the system was flushed before the next chamber closed. Each AFC-FTIR system was calibrated three times a day against a standard gas (1 ppm N<sub>2</sub>O, 5 ppm CH<sub>4</sub>, 2000 ppm CO<sub>2</sub>) to reduce measurement bias from the analyzers. One port on each multiplexer sampled outside air as an ambient air standard as well. Soil temperature and moisture probes (8150-203 and 8150-202, Li-Cor Biosciences, Lincoln, NB) were connected to auxiliary sensor inputs on each chamber and data was recorded during each gas flux measurement. Gas fluxes were calculated using the HMR model (Pedersen et al., 2010); i.e. a modification of the Hutchinson and Mosier method (Hutchinson and Mosier, 1981) that fits the gas concentration vs. time data to exponential or linear regression equations. The data was run in Python (Python(x,y) version 2.7.9, 2014) but follows the methods used in the R package developed by Pedersen (2017) (Appendix G). Python was used because it is better suited to running the large data sets produced with the AFC-FTIR system and is able to run the flux data for multiple gases at the same time. Cumulative emissions were calculated using an AUC analysis. The addition of automated chamber data allowed comparison of the effect of sampling intensity on the seasonal flux estimates used to calculate GHG emissions from agricultural soils.

The chambers for the AFC-FTIR system were removed during the winter and replaced in the spring to capture the fluxes during the spring melt, after which the equipment was set up at the next study site after seeding. Automated sampling data is available only to June 30, 2016, when lightning activity in the area damaged the electronics.

### **3.3 Ancillary measurements**

Before seeding in the spring, the soil was sampled to 1 m, taking three cores from each plot that were divided into 0–10, 10–25, 25–50, 50–75, and 75–100 cm increments. In the fall, soil was sampled to 120 cm with three cores per plot from the harvest area, divided into intervals of 0–30, 30–60, 60–90, and 90–120 cm. All soil samples were analyzed for inorganic nitrogen content using a 2M KCl extraction (Maynard et al., 2008) followed by colorimetric analysis (Technicon AutoAnalyser; Seal Analytical Ltd., Mequon, WI) for NO<sub>3</sub> and NH<sub>4</sub> content. Ancillary measurements taken at the end of each growing season included aboveground biomass, seed yield, and seed and residue nitrogen content. One metre square samples of the crop were harvested from each plot, then dried and weighed at the U of S. Each sample was threshed in a stationary thresher, the seed weighed and a sample of straw ground. Subsamples of the seed and straw were analyzed using acid digestion (Thomas et al., 1967), followed by colorimetric analysis (Technicon AutoAnalyser; Seal Analytical Ltd., Mequon, WI) to determine the N content. The yields presented were from the combine harvest of the larger plot area, which was more representative of yield than the m<sup>2</sup>-samples.

### **3.4 Statistics**

Nitrous oxide fluxes from soil are known to have highly variable and skewed distributions. Due to the extreme variability in N<sub>2</sub>O emissions, the risk of a type II error can be high; therefore, an alpha value of 0.10 was used to determine significance unless otherwise stated. Data were tested for normal distribution with D'Agostino-Pearson K<sup>2</sup> test. Data that did not have a normal distribution was Log<sub>10</sub> transformed before analysis and back transformed for presentation in tables and graphs. Treatment effects were determined by two-way analysis of variance (ANOVA) of

cumulative emissions with year and treatment as factors, and Tukey's HSD was used to compare treatment means. A one-way ANOVA with contrasts was done for the automated and manual cumulative emissions, as well as the cumulative emissions in terms of rate, timing, and placement treatments (Appendix D). Statistical analyses were done using CoStat software (version 6.4, CoHort software, Monterey, CA).

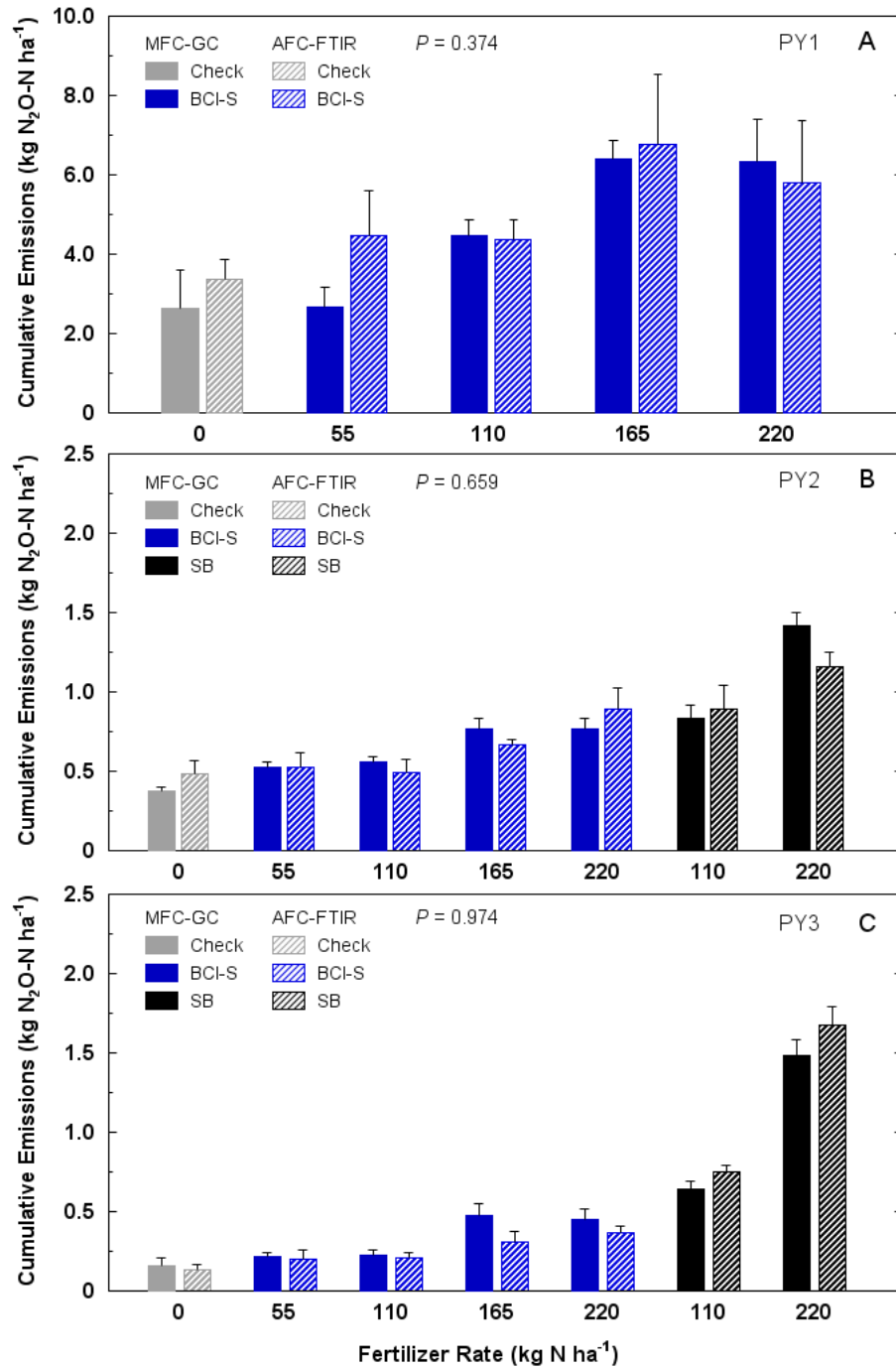
## 4. RESULTS

### 4.1 Manual sampling vs. automated sampling

During this study, manual (MFC-GC) and automated (AFC-FTIR) sampling systems were used to monitor emissions at intervals ranging from several times per day (automated sampling), to two or three times a week or less frequently (manual sampling). The automated systems consisted of a Fourier Transform Infra-Red (FTIR) gas analyzer connected to a series of automated flux measurement chambers (AFC) that were set up in a subset of the treatment plots, which were also manually sampled. The number of samples taken per chamber from each system for each year of the study is presented in Table 4.1. The AFC-FTIR system has an extremely high temporal density compared to MFC-GC; however, a comparison of the cumulative emissions from the two methods showed no significant difference between them from all years (Fig. 4.1). Consequently, only the results from the manual sampling are presented in this thesis.

**Table 4.1.** The number of samples taken from automated (AFC-FTIR) and manual (MFC-GC) sampling systems during the production year. Note: AFC-FTIR system was damaged and unable to collect data after June 28, 2016.

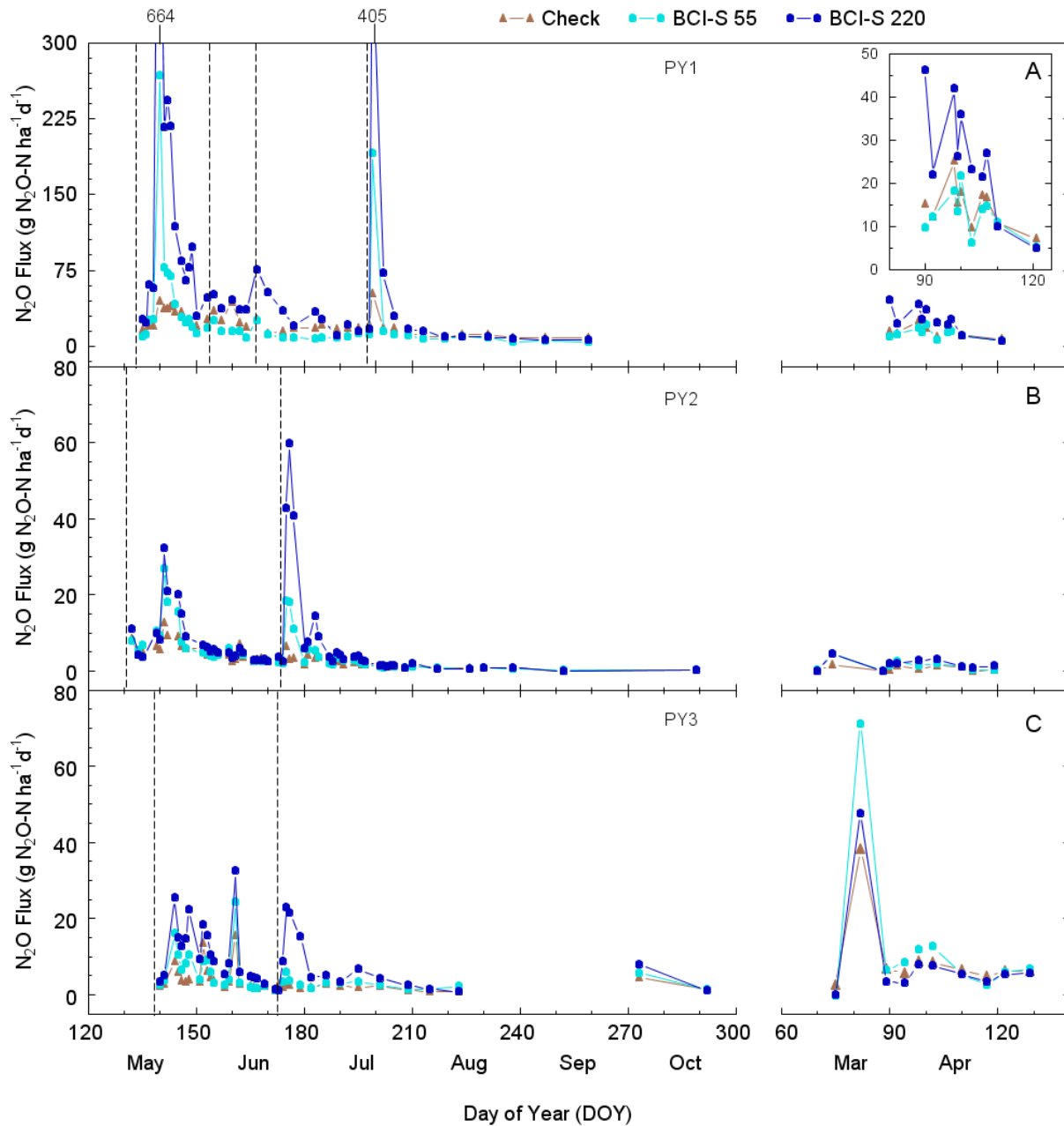
Sampling system	Number of samples taken (per chamber)		
	PY1	PY2	PY3
AFC-FTIR	1149–1166	1294–1359	140–142
MFC-GC	51	66	46



**Figure 4.1.** Comparison of the cumulative N<sub>2</sub>O emissions from manual (MFC-GC) and automated (AFC-FTIR) flux chamber systems in (A) PY1 (2014/15), (B) PY2 (2015/16), and (C) PY3 (2016/17). There were no significant differences between MFC and AFC data at the  $P = 0.05$  level of probability. Error bars indicate standard error of the mean ( $n = 3$ ). Additional AFC-FTIR chambers were added to the side-banded (SB) plots for 2015 and 2016. Data for 2016 was from the beginning of the growing season only, ending on June 28 when the AFC-FTIR system was damaged.

## 4.2 Effect of N rate

For all N rates, daily N<sub>2</sub>O emissions followed a similar trend, with an emission event that lasted eight to twelve days after the first fertilizer application, followed by a period of reduced emissions with small peaks after irrigation or precipitation events, and a second large emission event after the mid-season fertilizer application that lasted six to ten days (Fig. 4.2). The highest rate of N fertilizer did not always produce the greatest N<sub>2</sub>O emissions; five to nine days after seeding/fertilizer application, the first large peaks occurred from the 165 kg N ha<sup>-1</sup> rate in all three years (807 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> in PY1, 34 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> in PY2, and 33 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> in PY3). In PY1, establishment of the crop was poor so re-seeding occurred twice, on June 3 (DOY 154), which led to a small emission peak, and on June 16 (DOY 167) where a more pronounced peak occurred (Fig. 4.2), likely caused by the soil disturbance from reseeded and the irrigation that was subsequently applied. Large fluxes were measured after the top dress fertilizer application of the BCI-S treatments followed by irrigation, with the largest from the 220 kg N ha<sup>-1</sup> rate in PY2 and 3, and 165 kg N ha<sup>-1</sup> in PY1. Smaller emission peaks occurred after some irrigation or rainfall events. The 55 kg N ha<sup>-1</sup> rate consistently had the lowest emissions, similar to the check (0 N) in PY1, except after fertilizer applications when the fertilized plots had a distinct emission peak. After the top dress fertilizer application, emissions were low until the soil froze. Average emissions during this period ranged from 4.2 to 17 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 9.0 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) in PY1, 0 to 1.8 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 0.9 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) in PY2, and 0.8 to 9.0 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 3.4 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) in PY3.

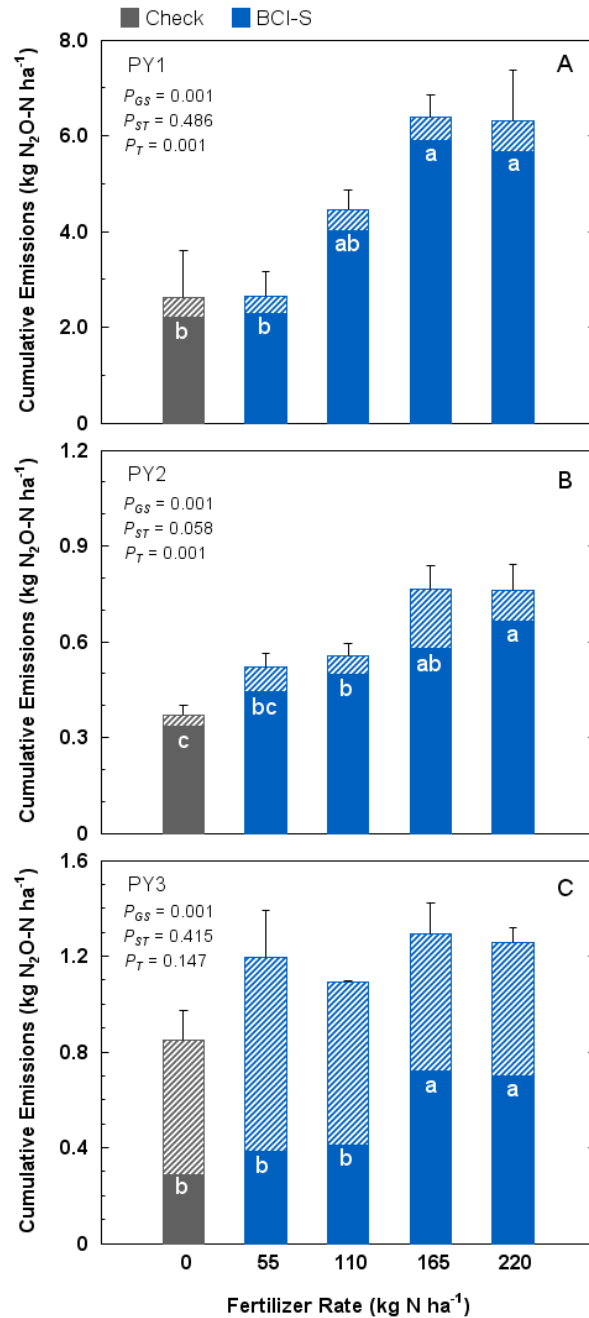


**Figure 4.2.** The average daily  $N_2O$  flux that shows the effect of the rate of urea fertilizer from the split broadcast and incorporated (BCI-S) treatments for (A) PY1 (2014/15), (B) PY2 (2015/16) and (C) PY3 (2016/17). Gas samples were collected using the manual flux chamber (MFC) system and analyzed using gas chromatography (GC). The dashed lines represent seeding/fertilizer application and application of top dress N. Note: the middle two lines in PY1 are additional seeding operations but no additional fertilizer was added.



The subsequent daily spring fluxes in PY1 occurred as multiple peaks that gradually reduced in magnitude over the sampling period (Fig. 4.2). In PY2 and PY3, there was one large initial peak following the main thaw event, and then emissions were relatively low, but greater than the emissions from the end of the growing season. Emissions during the spring thaw period were similar regardless of N fertilizer rate, ranging from 5 to 46 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 18 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) in PY1, -0.1 to 15 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 1.7 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) in PY2, and 2.5 to 16 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 7.2 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) in PY3.

Nitrogen fertilizer rate had a significant effect on the growing season cumulative N<sub>2</sub>O emissions ( $P = 0.002$  in PY1;  $P = 0.055$  in PY2;  $P = 0.022$  in PY3) (Appendix D). In the first two years, the 165 and 220 kg N ha<sup>-1</sup> rates had significantly higher cumulative emissions than the check and 55 kg N ha<sup>-1</sup> rate, whereas cumulative emissions from the 110 kg N ha<sup>-1</sup> application were between the high and low rates (PY1) or the same as 55 kg N ha<sup>-1</sup> (PY2) (Fig. 4.3). When looking at only the growing season emissions the trends in PY3 were similar to PY1 and PY2, where the emissions from the two highest rates were significantly greater than the check, 55 and 110 kg N ha<sup>-1</sup> rates. However, when the spring emissions were included these trends disappeared, and the total cumulative emissions were not significantly different for any N rate in PY3 (Fig. 4.3). The spring cumulative emissions were not affected by the N fertilizer rates that were applied in the previous growing season. Spring emissions were low relative to those during the growing season in PY1 and PY2, however in PY3, they were comparable to, or greater than, the emissions from the growing season.



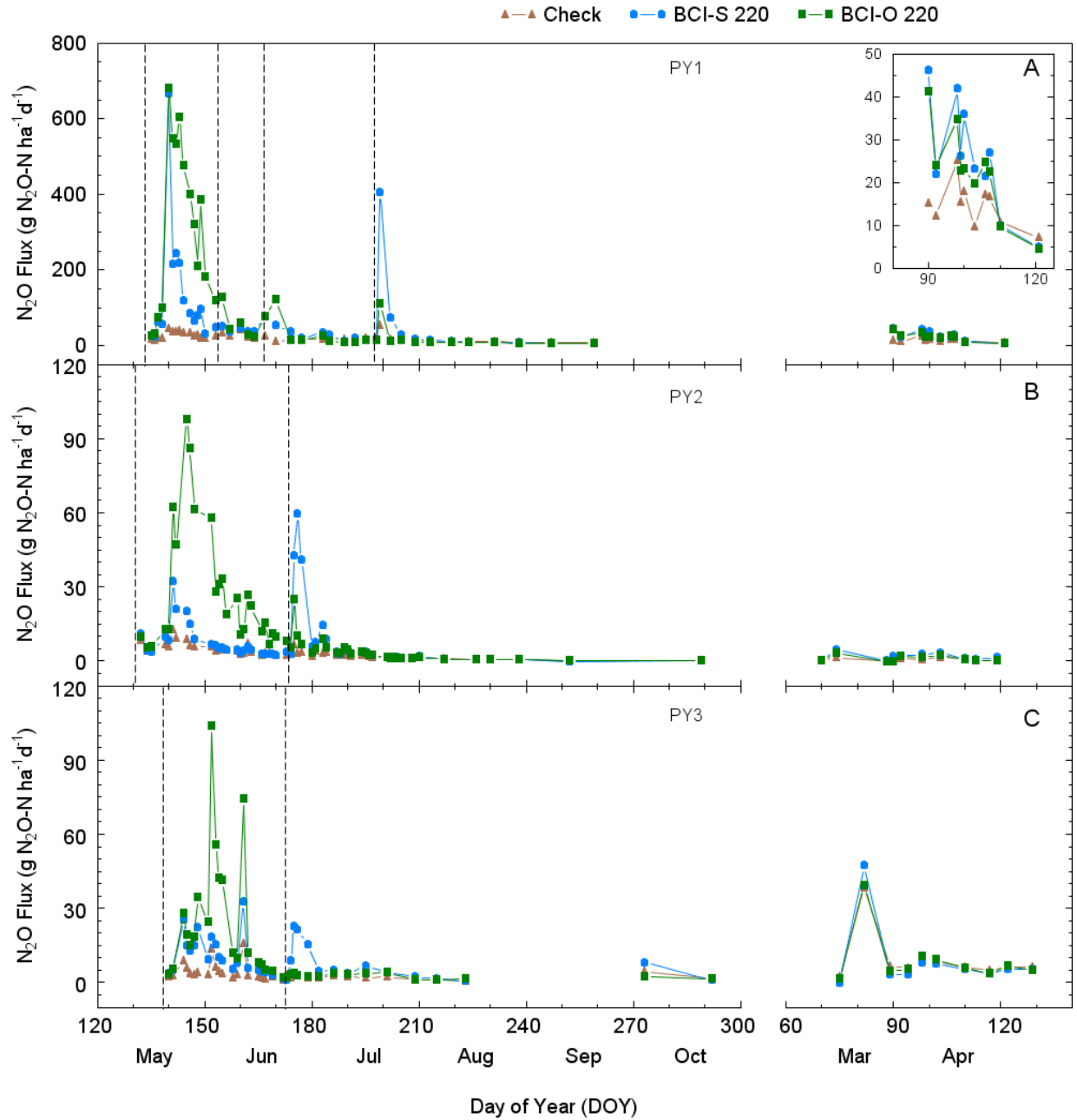
**Figure 4.3.** Effect of rate of urea fertilizer on cumulative N<sub>2</sub>O emissions for (A) PY1 (2014/15), (B) PY2 (2015/16), and (C) PY3 (2016/17). Gas samples were collected from manual flux chambers (MFC) and analyzed with gas chromatography (GC). Bars with the same letter represent growing season emissions that are not significantly different at  $P = 0.05$ . Notes: (i) the solid bars represent growing season (GS) emissions and the shaded represents the following spring thaw (ST); (ii) error bars indicate standard error of the mean ( $n = 3$ ); (iii) all plots received the same tillage operations as the BCI-S plots; and (iv) half the fertilizer N was applied prior to seeding (broadcast and incorporated), and half as a top dress prior to bolting.

There was a rate component for the N timing and placement treatments as well, where 110 and 220 kg N ha<sup>-1</sup> were compared. Overall, the check plots had the lowest cumulative N<sub>2</sub>O emissions, the 220 kg N ha<sup>-1</sup> had the greatest emissions, and the cumulative emissions from the 110 kg N ha<sup>-1</sup> rate were in between. Further information about these treatments is presented in the following sections.

### **4.3 Effect of N timing**

To determine the effect that timing of fertilizer application had on N<sub>2</sub>O emissions, one-time (BCI-O) and split (BCI-S) broadcast and incorporated applications of urea were compared at total N rates of 110 and 220 kg ha<sup>-1</sup>. For the BCI-O application, urea was applied just before seeding. For the BCI-S application, half of the total fertilizer (55 and 110 kg N ha<sup>-1</sup>) was applied before seeding, and the remaining half was applied as a top dress before bolting of the canola.

Daily N<sub>2</sub>O emissions from the BCI-O and BCI-S treatments followed the same overall pattern, where emissions began to increase several days after fertilizer application, with the period of peak emissions lasting two to three weeks, depending on treatment. The initial emission event associated with the spring N application was larger and lasted longer when all the N was applied at seeding (Fig. 4.4), which would be expected, as the BCI-S treatment had half the amount of fertilizer applied at that time. The top dress fertilizer application for the BCI-S treatments occurred four to eight weeks after the initial application, which resulted in another large emission event. A small peak also occurred from the BCI-O treatments at this time likely caused by the irrigation that accompanied the top dress N application, which occurred across the whole site, although fertilizer was only applied in the BCI-S plots. The largest fluxes were from BCI-O 220 kg N ha<sup>-1</sup>, reaching 679 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> in PY1, and close to 100 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> in PY2 and PY3. About a week

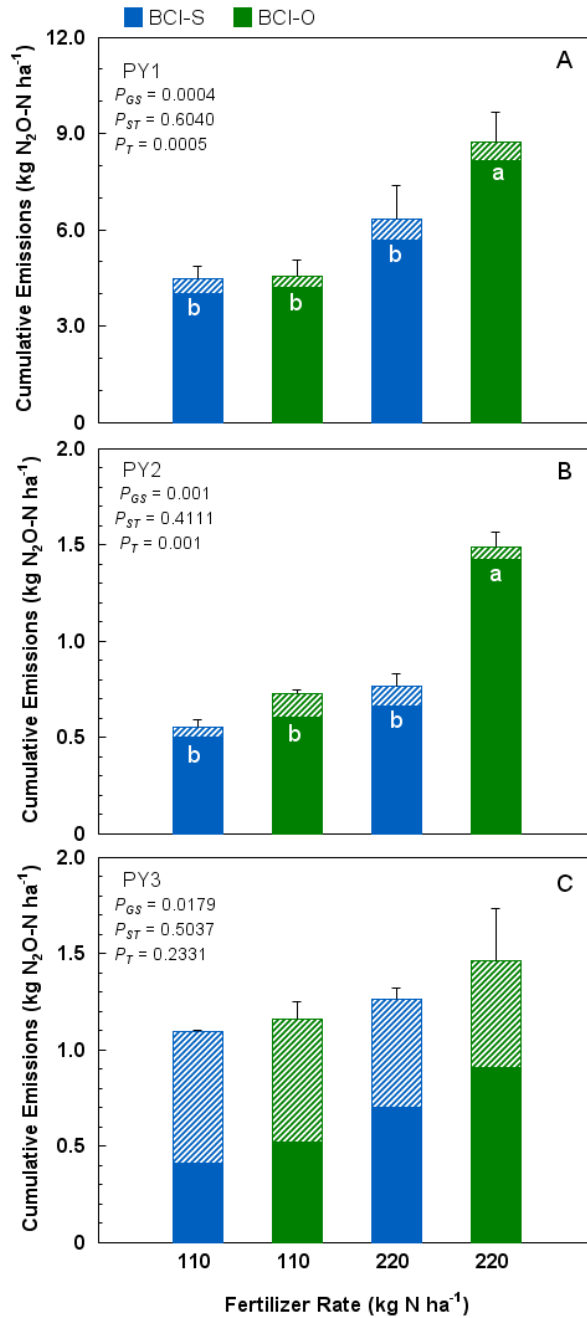


**Figure 4.4.** Average daily  $N_2O$  emissions from the fertilizer timing treatments (BCI-S and BCI-O at  $220 \text{ kg N ha}^{-1}$ ) for (A) PY1 (2014/15), (B) PY2 (2015/16) and (C) PY3 (2016/17). Gas samples were collected using the manual flux chamber (MFC) system and analyzed using gas chromatography (GC). The dashed lines represent seeding/initial fertilizer applications and applications of top dress N. Note: the middle two lines in PY1 are additional seeding operations but no additional fertilizer was added.

after the top dress N application, emissions from all treatments were low until the soil froze, ranging from 4 to 17 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup> ( $\bar{x}$  = 8.4 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>) in PY1, 0 to 1.8 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 0.9 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) in PY2, and 0.8 to 8 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 3.0 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>) in PY3 (Fig. 4.4).

Spring emissions in PY1 occurred as multiple peaks that gradually decreased in magnitude over the sampling period for both timing applications. There was no significant difference in emissions between the treatments, and the average N<sub>2</sub>O fluxes ranged from 4.3 to 46 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup> ( $\bar{x}$  = 20 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>). Spring emissions from PY2 were the lowest of all three years and the only significant difference in emissions was between the check and BCI-O 110 kg N ha<sup>-1</sup>. There was one peak event in March, after which average emissions ranged from -0.3 to 4.7 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup> ( $\bar{x}$  = 1.4 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>) (Fig. 4.4). In the spring of PY3, cumulative emissions were high in comparison to the growing season. There was one large peak in late March, after which emissions ranged from 3.1 to 16 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup> ( $\bar{x}$  = 7.1 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>).

Timing of fertilizer application affected cumulative emissions in the growing season in all years but had no effect on the spring cumulative emissions. The growing season cumulative emissions are the most important when looking at the treatment effects because the spring emissions are relatively independent of the applied treatments from the previous year. When looking at the two N rates separately, splitting the urea had no significant effect on growing season cumulative emissions at the lower total N rate of 110 kg N ha<sup>-1</sup> ( $P$  = 0.70 in PY1,  $P$  = 0.14 in PY2, and  $P$  = 0.32 in PY3), however, it significantly reduced growing season cumulative N<sub>2</sub>O emissions at 220 kg ha<sup>-1</sup> total N in two years of the study ( $P$  = 0.03 in PY1,  $P$  = 0.01 in PY2), but not in PY3 ( $P$  = 0.23) (Fig. 4.5).

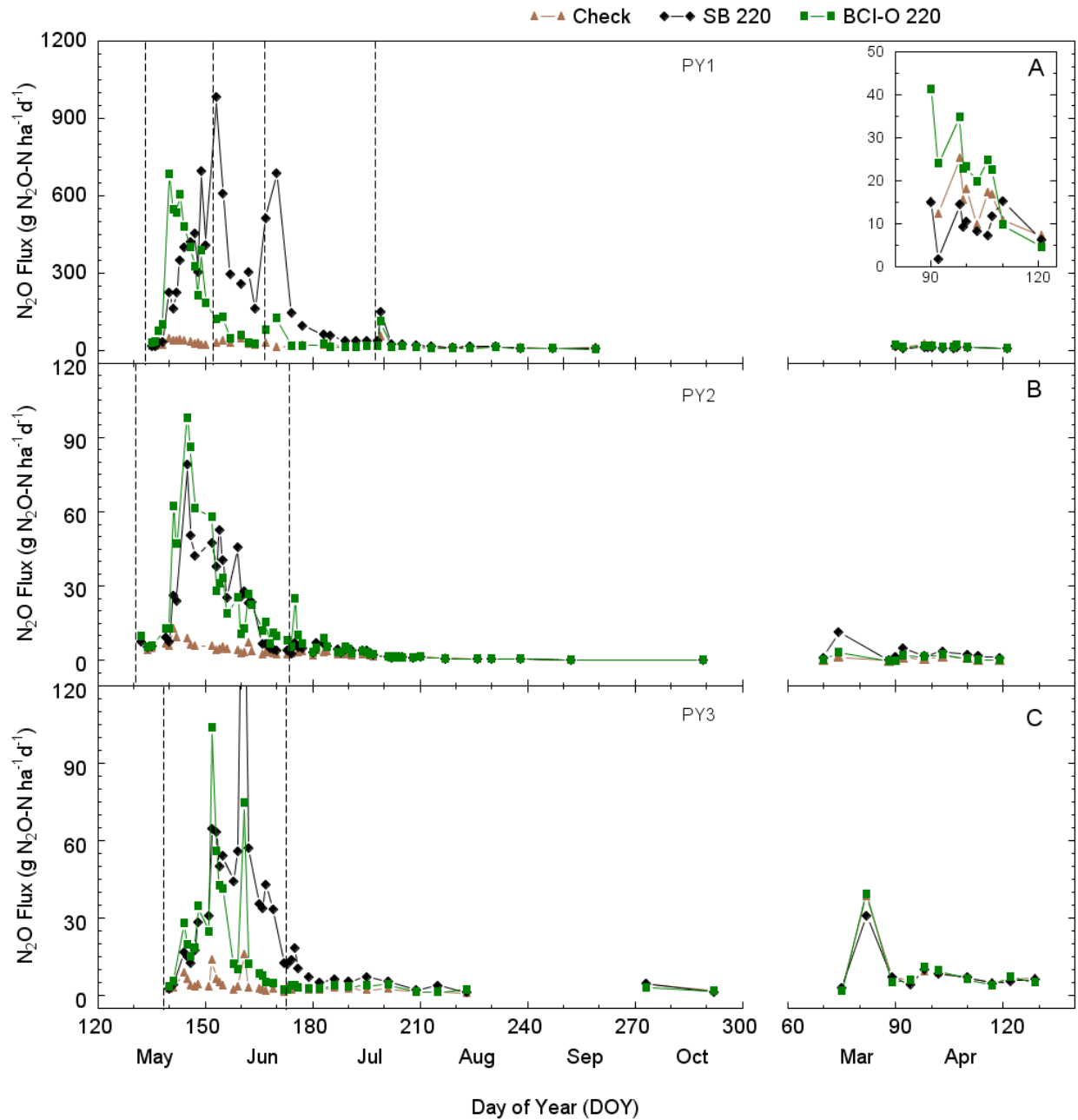


**Figure 4.5.** Effect of timing—split (BCI-S) vs. one-time (BCI-O) application of urea—on cumulative N<sub>2</sub>O emissions from (A) PY1 (2014/15), (B) PY2 (2015/16), and (C) PY3 (2016/17). Gas samples were collected using the manual flux chamber (MFC) system and analyzed using gas chromatography (GC). Bars with the same letter represent growing season emissions that are not significantly different at  $P = 0.05$ . Notes: (i) the solid bars represent growing season (GS) emissions and the shaded represents the following spring thaw (ST); (ii) error bars indicate standard error of the mean ( $n = 3$ ); (iii) half the fertilizer for the BCI-S plots was applied prior to seeding (broadcast-incorporated), half applied as a top dress prior to bolting.

#### 4.4 Effect of N placement

The daily flux trends differed depending on fertilizer N placement (Fig. 4.6). In PY1 and PY2, emissions from the BCI-O treatments began to increase several days after N application and reached a peak one to two weeks later. The SB treatments tended to have a lag time of several days, and emissions gradually increased to the maximum N<sub>2</sub>O flux two to three weeks after fertilizer application. The largest N<sub>2</sub>O fluxes were 984 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> from SB 220 kg ha<sup>-1</sup> in PY1, 98 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> from BCI-O 220 kg ha<sup>-1</sup> in PY2, and 236 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> from SB 220 kg ha<sup>-1</sup> in PY3. In PY1, another large peak occurred in mid-June when the plots were re-seeded and irrigated. In PY2, the BCI-O and SB emissions followed a very similar pattern at both rates, and the N<sub>2</sub>O peaks were very similar between these treatments (Fig. 4.6). In all years, a small but distinct emission event occurred after the irrigation that accompanied the top dress N application, which occurred across the whole site, however fertilizer was only applied in the BCI-S plots. Emissions remained relatively low for the remainder of the growing season, with average fluxes ranging from 4 to 20 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 9.2 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>) in PY1, 0.1 to 1.7 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 0.9 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>) in PY2, and 0.6 to 7 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 2.9 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>) in PY3.

There were no significant differences in spring N<sub>2</sub>O emissions between N placement in any of the study years. The spring fluxes in PY1 occurred as multiple peaks that gradually reduced in magnitude over the sampling period (Fig. 4.6), and the average N<sub>2</sub>O emissions ranged from 1.5 to 41 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 14 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>). Spring emissions in PY2 and PY3 had one peak in mid to late March and relatively low fluxes afterwards, that ranged from -0.3 to 12 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 2.0 g N<sub>2</sub>O-N ha<sup>-1</sup>d<sup>-1</sup>), and 3.2 to 16 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> ( $\bar{x}$  = 7.1 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup>) respectively.



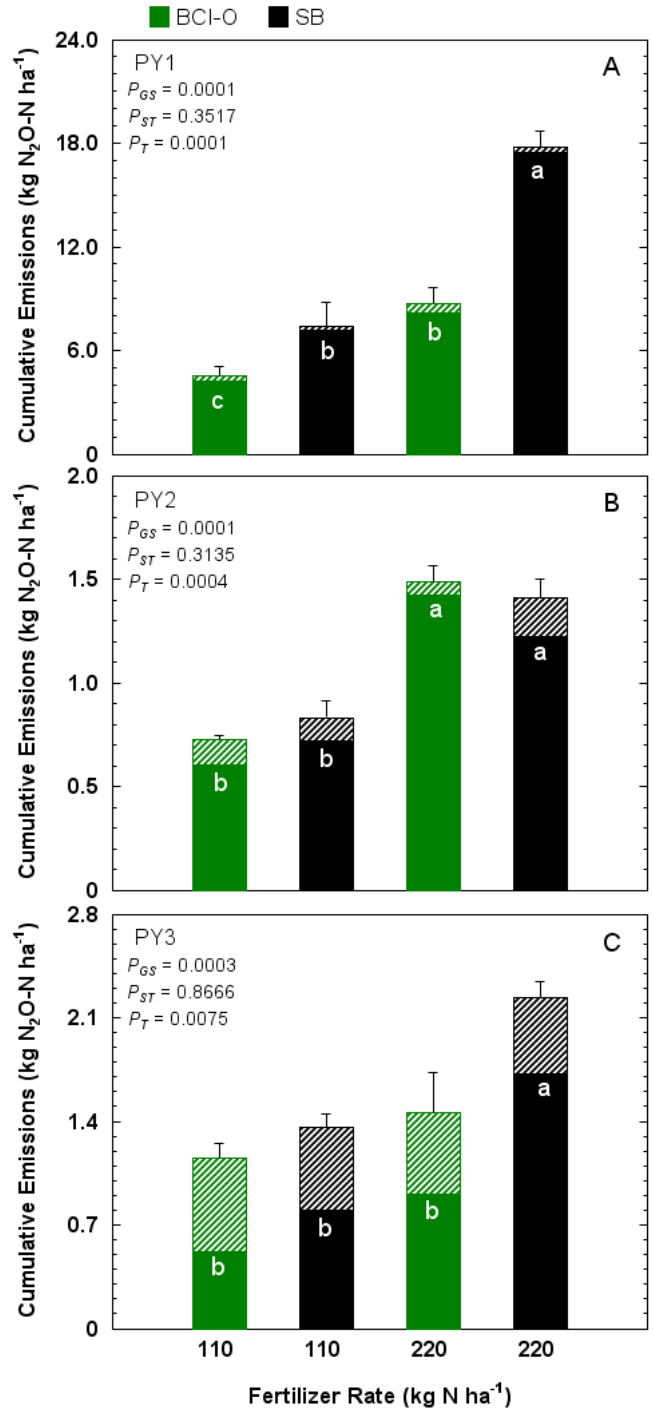
**Figure 4.6.** Average daily  $N_2O$  emissions from the fertilizer placement treatments (SB and BCI-O at  $220 \text{ kg N ha}^{-1}$ ) for (A) PY1 (2014/15), (B) PY2 (2015/16) and (C) PY3 (2016/17). Gas samples were collected using the manual flux chamber (MFC) system and analyzed using gas chromatography (GC). The dashed lines represent seeding/initial fertilizer applications and applications of top dress N. Note: the middle two lines in PY1 are additional seeding operations but no additional fertilizer was added.



The effect of fertilizer placement on growing season cumulative emissions was significant in PY1 and PY3, but not in PY2 (Fig. 4.7). Cumulative emissions were greater from the SB application than the BCI-O treatment at both rates in PY1, and SB 220 kg N ha<sup>-1</sup> had close to twice the growing season cumulative N<sub>2</sub>O emissions of BCI-O 220 kg N ha<sup>-1</sup>. However, the difference in emissions between SB and BCI-O 110 kg N ha<sup>-1</sup> were not as extreme. In PY2, N<sub>2</sub>O emissions from SB and BCI-O were equivalent at both N rates; there was no significant effect of fertilizer placement on growing season cumulative emissions ( $P = 0.46$ ). In PY3, SB was only significantly greater than BCI-O at the high N rate (220 kg N ha<sup>-1</sup>) and differences in the cumulative emissions were seen during the growing season and total emissions, but not during the spring (Fig. 4.7). The SB 220 kg N ha<sup>-1</sup> treatment had the highest emissions, while emissions from the 110 kg N ha<sup>-1</sup> rate were not significantly different than the check plots. The BCI-O 220 kg N ha<sup>-1</sup> treatment had growing season emissions that were between the check and SB 220 kg N ha<sup>-1</sup>.

#### **4.5 Seed yield and nitrogen uptake**

Average seed yield in the non-fertilized plots ranged from 1996 kg ha<sup>-1</sup> (35.5 bu ac<sup>-1</sup>) in 2014 to 3427 kg ha<sup>-1</sup> (61.1 bu ac<sup>-1</sup>) in 2016. Poor yields in PY1 (Table 4.2) were due to poor stand establishment that necessitated re-seeding twice. The last seeding took place in mid-June and the yield was likely reduced by frost damage to the crop in September. Application of N fertilizer had no significant effect on yield in PY1 or PY3, but in PY2 the N treatments increased the yield compared to the check plots. The inter-annual differences in yield are also significant ( $P = 0.10$ ), with yields increasing with each year of the study.



**Figure 4.7.** Effect of urea fertilizer placement (BCI-O vs. SB) on cumulative N<sub>2</sub>O emissions from (A) PY1 (2014/15), (B) PY2 (2015/16), and (C) PY3 (2016/17). Gas samples were collected using the manual flux chamber (MFC) system and analyzed using gas chromatography (GC). Bars with the same letter represent growing season emissions that are not significantly different at  $P = 0.05$ . Note: the solid bars represent growing season (GS) emissions and the shaded represents the following spring thaw (ST).

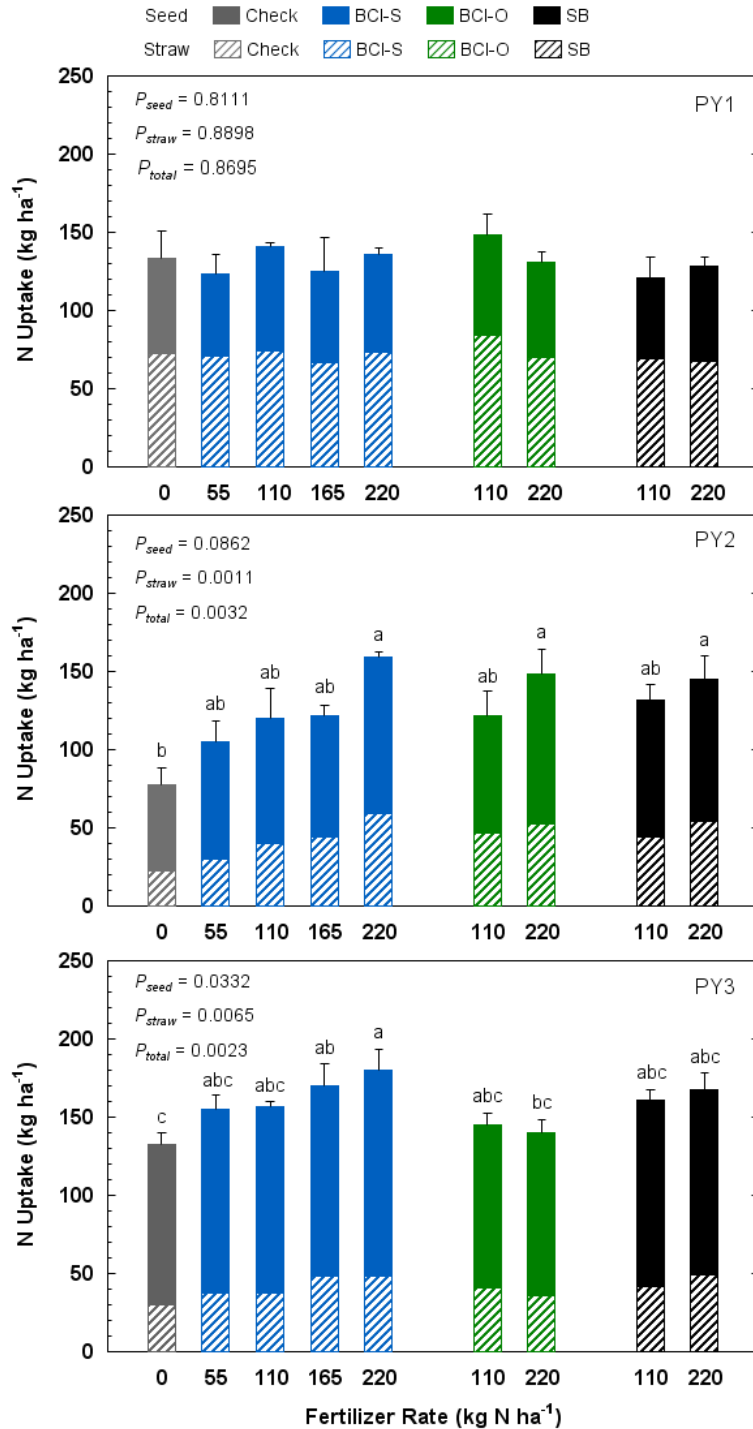
The overall trend in nitrogen uptake was that uptake increased with increased fertilizer N rate; however, the only significant difference was between the check and high N rate of 220 kg N ha<sup>-1</sup> for the BCI-S application (Fig. 4.8). For the timing (BCI-O) and placement (SB) treatments there was no significant difference in N uptake between the N rates. In PY1, total N uptake did not differ between treatments and nitrogen uptake in the straw was greater than in the other years, whereas uptake in the seed was lower (Fig. 4.8). This was likely due to the fall frost damage preventing translocation of N to the seed. The greatest N uptake in the seed was in PY3, which also had the highest total N uptake.

**Table 4.2.** Average seed yield from each treatment. The yield was corrected to 8.5% moisture.

Treatment	Rate	PY1†		PY2‡		PY3†	
		<i>kg ha<sup>-1</sup></i>	<i>bu ac<sup>-1</sup></i>	<i>kg ha<sup>-1</sup></i>	<i>bu ac<sup>-1</sup></i>	<i>kg ha<sup>-1</sup></i>	<i>bu ac<sup>-1</sup></i>
<b>Check</b>	0	1996 ± 571	35.6	2567 ± 323 b	45.8	3427 ± 273	61.1
<b>BCI-S</b>	55	2211 ± 690	39.4	3437 ± 280 a	61.3	3579 ± 216	63.8
	110	1940 ± 144	34.6	3639 ± 185 a	64.9	3700 ± 452	66.0
	165	2134 ± 530	38.1	3679 ± 16.2 a	65.6	3835 ± 262	68.4
	220	2363 ± 442	42.1	3609 ± 58.7 a	64.4	3735 ± 430	66.6
<b>BCI-O</b>	110	2185 ± 446	39.0	3583 ± 145 a	63.9	3674 ± 268	65.5
	220	2541 ± 540	45.3	3724 ± 437 a	66.4	3657 ± 199	65.2
<b>SB</b>	110	2088 ± 420	37.2	3516 ± 258 a	62.7	3835 ± 341	68.4
	220	2681 ± 338	47.8	3702 ± 177 a	66.0	3570 ± 337	63.7

† Not significant at  $P = 0.05$ ; values presented are mean and standard deviation ( $n = 4$ ).

‡ Values with the same letter are not significantly different at  $P = 0.05$ .



**Figure 4.8.** Total nitrogen uptake from seed (solid) and straw (shaded) from split broadcast and incorporated (BCI-S), broadcast and incorporated (BCI-O), and side-banded (SB) treatments in PY1 (2014/15), PY2 (2015/16), and PY3 (2016/17). Bars with the same letter are not significantly different at  $P = 0.05$  level of probability and error bars represent standard error of the mean ( $n = 3$ ).

#### 4.6 Emission factors

In general, fertilizer-induced emissions (FIE) increased with increasing N rate, though an exception occurred with the split N application, which yielded a significant difference only between the 220 kg N ha<sup>-1</sup> and 55 kg N ha<sup>-1</sup> rates in 2014 (Table 4.3). Fertilizer-induced emissions were greatest at the highest application rate (220 kg N ha<sup>-1</sup>) regardless of whether the N was applied as a side-band or broadcast and incorporated. As well, there was a significant treatment effect on the emission factor (EF) in two of the three years of the study (i.e., 2014 and 2015). In 2014, the EFs for both rates of the SB treatment were significantly greater than those for BCI-O and BCI-S treatments. The yield-scaled emission factors (YsEF) were similar to FIE in that the highest values occurred in 2014 and were generally greater at the highest N application rate (220 kg N ha<sup>-1</sup>) when the N was applied as either a side-band or was broadcast and incorporated.

**Table 4.3.** Fertilizer induced emissions (FIE), emission factor (EF), and yield-scaled emission factor (YsEF) values.

Treatment	N rate <sup>†</sup> (kg ha <sup>-1</sup> )	FIE <sup>‡</sup> (kg N <sub>2</sub> O-N ha <sup>-1</sup> )			EF (%) <sup>‡</sup>			YsEF <sup>‡</sup> (g N <sub>2</sub> O-N kg <sup>-1</sup> seed)		
		2014	2015	2016	2014	2015	2016 <sup>§</sup>	2014	2015	2016
<b>Check</b>	<b>0</b>	-	-	-	-	-	-	1.55 bc	0.15 b	0.25 b
<b>Split Broadcast - Incorporated (BCI-S)</b>	<b>55</b>	0.03 d	0.14 b	0.34 b	0.06 d	0.26 bcd	0.63	1.39 c	0.15 b	0.34 b
	<b>110</b>	1.84 cd	0.18 b	0.24 b	1.68 cd	0.16 d	0.22	2.33 bc	0.15 b	0.30 b
	<b>165</b>	3.78 bc	0.37 b	0.44 b	2.29 bcd	0.22 cd	0.27	3.14 bc	0.20 b	0.34 b
	<b>220</b>	3.70 bc	0.36 b	0.41 b	1.68 cd	0.16 d	0.18	2.73 bc	0.21 b	0.34 b
<b>Broadcast - Incorporated (BCI-O)</b>	<b>110</b>	1.93 cd	0.35 b	0.30 b	1.75 cd	0.32 abcd	0.28	2.21 bc	0.20 b	0.32 b
	<b>220</b>	6.11 b	1.17 a	0.61 b	2.78 bc	0.53 a	0.28	3.47 bc	0.41 a	0.40 b
<b>Side-banded (SB)SB)</b>	<b>110</b>	4.81 bc	0.48 b	0.51 b	4.37 b	0.44 abc	0.46	3.63 b	0.23 b	0.36 b
	<b>220</b>	15.15 a	1.11 a	1.38 a	6.88 a	0.51 ab	0.63	6.76 a	0.38 a	0.63 a

<sup>†</sup> Total amount of N applied.

<sup>‡</sup> Within columns, means (n = 4) followed by the same letter are not significantly different ( $P = 0.05$ ).

<sup>§</sup> No significant ( $P = 0.05$ ) differences.

## 5. DISCUSSION

Nitrous oxide is a potent greenhouse gas, and the agricultural sector contributes more than 80% of Canada's N<sub>2</sub>O emissions annually. Nitrous oxide emissions are primarily controlled by soil N availability and soil moisture conditions. Large N<sub>2</sub>O fluxes frequently occur during spring thaw and after precipitation or irrigation events when the soil is saturated. Nitrous oxide emissions have very high spatial and temporal variability due to the complex interactions of N in the plant-soil N cycle (Chen et al., 2008). Spatial variability refers to how nitrous oxide emissions can vary widely over small or large areas due to the inherent heterogeneity of soil and how it interacts with several other factors that affect N<sub>2</sub>O emissions. Temporal variability refers to the fluctuation of N<sub>2</sub>O emissions over time, throughout the year or from one year to the next. Temporal resolution is the frequency of sampling that occurs over a specified period. For example, in my study the temporal resolution of manual gas sampling was low compared to the automated system, because manual sampling was done only several times per week, whereas sampling occurred multiple times per day with the automated system. The data has shown that manual sampling was still able to capture an accurate picture of the cumulative N<sub>2</sub>O emissions, especially when sampling was done strategically around events that have a high emission potential. Frequent sampling close to these events is more important than sampling at a high frequency over the whole season, especially late in the growing season when emissions tend to be low because there is generally less N available in the soil due to crop uptake. Data from the AFC-FTIR system provided a more detailed picture of N<sub>2</sub>O fluxes than manual sampling, which tended to overestimate peak periods and underestimate

low flux periods (Appendix B.1). However, over the sampling period they balanced out and the cumulative emissions did not differ significantly between methods. This outcome increased the confidence in the results from the manual sampling method, which was the primary method used to measure GHGs in every plot of the study.

Nitrogen fertilizer rate is one of the most important drivers of N<sub>2</sub>O emissions in cropping systems (Lemke et al., 1999; Linn and Doran, 1984). For the split N applications (BCI-S), the N applied at seeding was half of the total amount applied; i.e. 27.5, 55, 82.5, and 110 kg N ha<sup>-1</sup>, with the same rate applied as a top dress before bolting. These N rates were well below the recommended rates from soil tests (121 kg N ha<sup>-1</sup> in 2014, 175 kg N ha<sup>-1</sup> in 2015, and 189 kg N ha<sup>-1</sup> in 2016). After the initial fertilizer application and when the top dress N was applied, crop demand exceeded soil N availability, so the crop likely used the fertilizer N before it could be converted to N<sub>2</sub>O. The cumulative emissions from the growing season of PY3 followed a similar trend as the other years in which overall, emissions increased with increasing N rate. However, very high emissions the following spring resulted in total cumulative emissions that did not differ significantly between N rates. Izaurre et al. (2004) found that N<sub>2</sub>O emissions did not increase when N was applied at the recommended rate (45 kg N ha<sup>-1</sup>) compared to plots that did not receive fertilizer, but when the N rate exceeded the recommended rate of fertilizer the emissions were much greater. Emissions from the 55 kg N ha<sup>-1</sup> rate in this study were never higher than the check plots and the yields were not significantly lower than the higher N rates, which indicates that this rate was what the canola crop required for the conditions at the site. The 110 kg N ha<sup>-1</sup> rate is typical for dryland canola (Government of Saskatchewan, 2017a), but less than what ICDC (2017) recommends for irrigated canola. The average N uptake was 131 kg in PY1, 125 in PY2, and 156 in PY3. The 110 kg N ha<sup>-1</sup> rate is below the N requirements from the crop; however, additional N



would be provided from residual nitrate and organic-N mineralization in the soil. The cumulative emissions for this rate were not significantly greater than the check or 55 kg N ha<sup>-1</sup> rate, likely because the available N was very close to the amount required by the crop. Problems establishing the 2014 crop make it likely that N was susceptible to losses of N<sub>2</sub>O because the crop was not growing and therefore, it was not using the N available in the soil. The spring N<sub>2</sub>O emissions were not affected by the N fertilizer treatments from the previous growing season in any year and were not significantly different than the check plots. In general, spring N<sub>2</sub>O emissions were variable and greater than the background emissions from the end of the previous growing season. The emissions followed a pattern; a large flux event followed the initial thaw, and smaller emissions peaks occurred after other periods of freeze-thaw activity (Fig. 4.2)

Robertson and Vitousek (2009) stated that the single greatest contributor to loss of excess N in cropping systems is when the timing of N availability and crop demand do not match, and to rectify this, N should be added in multiple small applications when plant demand is high. However, this is generally impractical for producers. In practice, two N applications can help match plant uptake more effectively: once at seeding and then several weeks later when the crop is in a stage of rapid growth (Robertson and Vitousek, 2009). While the BCI-S and BCI-O fertilizer treatments received the same total amount of N fertilizer, the split treatments received only half of the fertilizer at seeding. This means that the BCI-S treatments only received 55 and 110 kg N ha<sup>-1</sup> of urea at seeding and at the top dress application four to six weeks later when the canola was bolting. The N<sub>2</sub>O emissions increased following the top dress (mid-season) application of urea, and the magnitude and duration of those emissions increased with increasing N rates. The N<sub>2</sub>O flux from the top dress application was much smaller than after the initial (pre-seeding) N application in PY1. In PY2 the top dress flux was greater, and in PY3 they had a similar magnitude (Fig. 4.4).

However, even at the highest N rate, crop demand was apparently great enough that N was rapidly used up—limiting the N available for microbial conversion to N<sub>2</sub>O (McSwiney and Robertson, 2005). In terms of cumulative emissions, splitting the fertilizer reduced N<sub>2</sub>O emissions compared to a single application of fertilizer, but only at the high N rate (i.e. 220 kg N ha<sup>-1</sup>) in 2014 and 2015. In 2016 the BCI-S treatments had slightly lower cumulative emissions than BCI-O, but the reduction was not significant. Allen et al. (2010) reported similar results in Australian sugarcane, wherein splitting the N over two applications reduced N<sub>2</sub>O emissions only at the highest N rate (220 kg N ha<sup>-1</sup>). In all years of the study, the cumulative emissions from BCI-O 110 kg N ha<sup>-1</sup> and BCI-S 220 kg N ha<sup>-1</sup> treatments were not significantly different. This is likely because the initial amount of fertilizer applied at seeding was the same and when the top dress fertilizer was applied several weeks later, either the growing crop could take it up or soil conditions were less conducive to N<sub>2</sub>O production during this time. The spring emissions followed the same pattern as the N rate treatments described previously, where the emissions peaked during the main freeze-thaw period, followed by some smaller emission events related to freeze-thaw activity. Emissions eventually declined to background levels, although these are greater than the background levels from the end of the growing season of the previous year (Fig. 4.4).

The effect that fertilizer placement had on N<sub>2</sub>O emissions was variable and was also affected by precipitation. Early season precipitation was greater than normal during the 2014 and 2016 growing seasons, and in these two years, the SB treatments had greater cumulative emissions than BCI-O at the 220 kg N ha<sup>-1</sup> rate, but not at the lower rate of 110 kg N ha<sup>-1</sup>. In 2015, less precipitation and lower soil moisture led to smaller (non-significant) differences in N<sub>2</sub>O emissions between the fertilizer placements, regardless of application rate. Cumulative emissions during PY2 and PY3 were within the range reported by other researchers (Burton et al., 2008a; Hultgreen and

Leduc, 2003), but were much lower than the emissions measured in 2014. Placing urea in a concentrated zone (e.g. side-banding) has been shown to improve N recovery by crops because the soil microbes have less contact with the fertilizer, which may reduce nitrification and slow the production of  $\text{NO}_3^-$  in the soil that can be lost through leaching or denitrification (Engel et al., 2010; Malhi et al., 2001; Yadvinder-Singh et al., 1994). Alternatively, concentrating urea in bands can increase  $\text{NO}_2^-$  accumulation in the soil, which may increase  $\text{N}_2\text{O}$  emissions (Venterea et al., 2012). Not surprisingly, previous studies have reported inconsistent results from banding urea: reduction of  $\text{N}_2\text{O}$  emissions compared to broadcast applications (Hultgreen and Leduc, 2003; Nash et al., 2012), increased emissions compared to broadcast applications (Cheng et al., 2002; Engel et al., 2010; Halvorson and Del Grosso, 2013), or emissions that are equivalent to broadcast applications (Burton et al., 2008a; Engel et al., 2010; Gao et al., 2017; Hultgreen and Leduc, 2003). A study by Engel et al. (2010) in Montana reported results similar to what is presented here; i.e., the banded fertilizer treatments produced similar  $\text{N}_2\text{O}$  emissions to the broadcast treatment at recommended rates of N fertilizer, but emissions were increased if N rates were above the recommended rate. This was attributed to a reduction in the rate of urea hydrolysis and inhibition of nitrification due to the concentrated band of urea which prolonged the period of  $\text{N}_2\text{O}$  production. Hultgreen and Leduc (2003) found a weak trend where  $\text{N}_2\text{O}$  emissions from broadcast treatments were higher than banded, though in most years of the study there were no differences between placements at three of the four sites across Saskatchewan. Based on the results from the current study and other researchers, it is difficult to determine if banding urea fertilizer is effective at reducing  $\text{N}_2\text{O}$  emissions for the conditions similar to this site.

Soil moisture, primarily from precipitation, had a substantial effect on  $\text{N}_2\text{O}$  emissions during all years of the study. During PY1, the cumulative emissions were as much as ten times

greater than the following two years. This was attributed to cold and wet soil at seeding that resulted in poor stand establishment. There was greater precipitation than average in PY1, particularly around the time the fertilizer was applied, which would have led to soil conditions that were conducive to high denitrification activity (Nyborg et al., 1997; Lemke et al., 1998). In 2014, the amount of snow on the ground reached a maximum of 40 cm on March 7, which would have contributed to high soil moisture in the spring when it melted (Environment Canada, 2018). The cumulative emissions from the check plots were also very high this year, indicating that there was a substantial amount of plant-available N in the soil. This was confirmed with a spring soil test that showed 63 kg available-N ha<sup>-1</sup> in the 0–30 cm depth and 245 kg N ha<sup>-1</sup> in the 30–60 cm depth. In 2015, precipitation was below average in May when fertilizer was applied, and in June (Appendix C.1) when it would have been highly susceptible to gaseous loss (Burton et al., 2008a; Halvorson and Del Grosso, 2013; Roy et al., 2014). This year required the most irrigation, with eight applications that ranged from 6-15 mm between the end of May and beginning of July. Table 5.1 shows the cumulative emissions from May to June compared to the total cumulative emissions and the percentage of the total that occurred during this period. Although 2015 had the lowest precipitation during those months, rainfall was supplemented with irrigation and a large portion of N<sub>2</sub>O emissions occurred during this period (58–87% of the total emissions). Post-fertilizer application is typically a period when a high percentage of N<sub>2</sub>O emissions occur (Burton et al., 2008; Dusenbury et al., 2008; Halvorson and Del Grosso, 2012). Indeed, except for some treatments in PY3, more than half of the cumulative emissions occurred in May and June. Above average rainfall occurred in July through October of 2015, but this had little impact on N<sub>2</sub>O emissions because the crop would have utilized much of the fertilizer by this time. This suggests that N availability controls the magnitude of N<sub>2</sub>O emissions and soil moisture triggers these large

**Table 5.1.** Summary of total cumulative N<sub>2</sub>O emissions and emissions from May to June of PY1(2014/15), PY2 (2015/16), and PY3 (2016/17). May to June is a period of high emissions post fertilizer application, and emissions from this period are shown in kg ha<sup>-1</sup> and the percentage of the total emissions from each production year.

Treatment	N Rate (kg ha <sup>-1</sup> )	2014			2015			2016		
		PY1 Total (kg ha <sup>-1</sup> )	May-June (kg ha <sup>-1</sup> )	%	PY2 Total (kg ha <sup>-1</sup> )	May-June (kg ha <sup>-1</sup> )	%	PY3 Total (kg ha <sup>-1</sup> )	May-June (kg ha <sup>-1</sup> )	%
<b>Check</b>	0	2.61	1.2	45	0.37	0.24	65	0.85	0.16	19
<b>BCI-S</b>	55	2.64	1.3	50	0.52	0.35	66	1.19	0.22	19
	110	4.46	2.3	51	0.55	0.38	69	1.09	0.23	21
	165	6.39	3.9	61	0.76	0.44	58	1.29	0.49	38
	220	6.32	3.8	60	0.76	0.52	68	1.25	0.47	38
<b>BCI-O</b>	110	4.54	3.3	74	0.72	0.48	66	1.15	0.35	31
	220	8.72	7.3	84	1.49	1.30	87	1.46	0.77	52
<b>SB</b>	110	7.42	6.1	82	0.83	0.61	73	1.36	0.65	48
	220	17.8	15.8	89	1.41	1.10	77	2.23	1.50	67

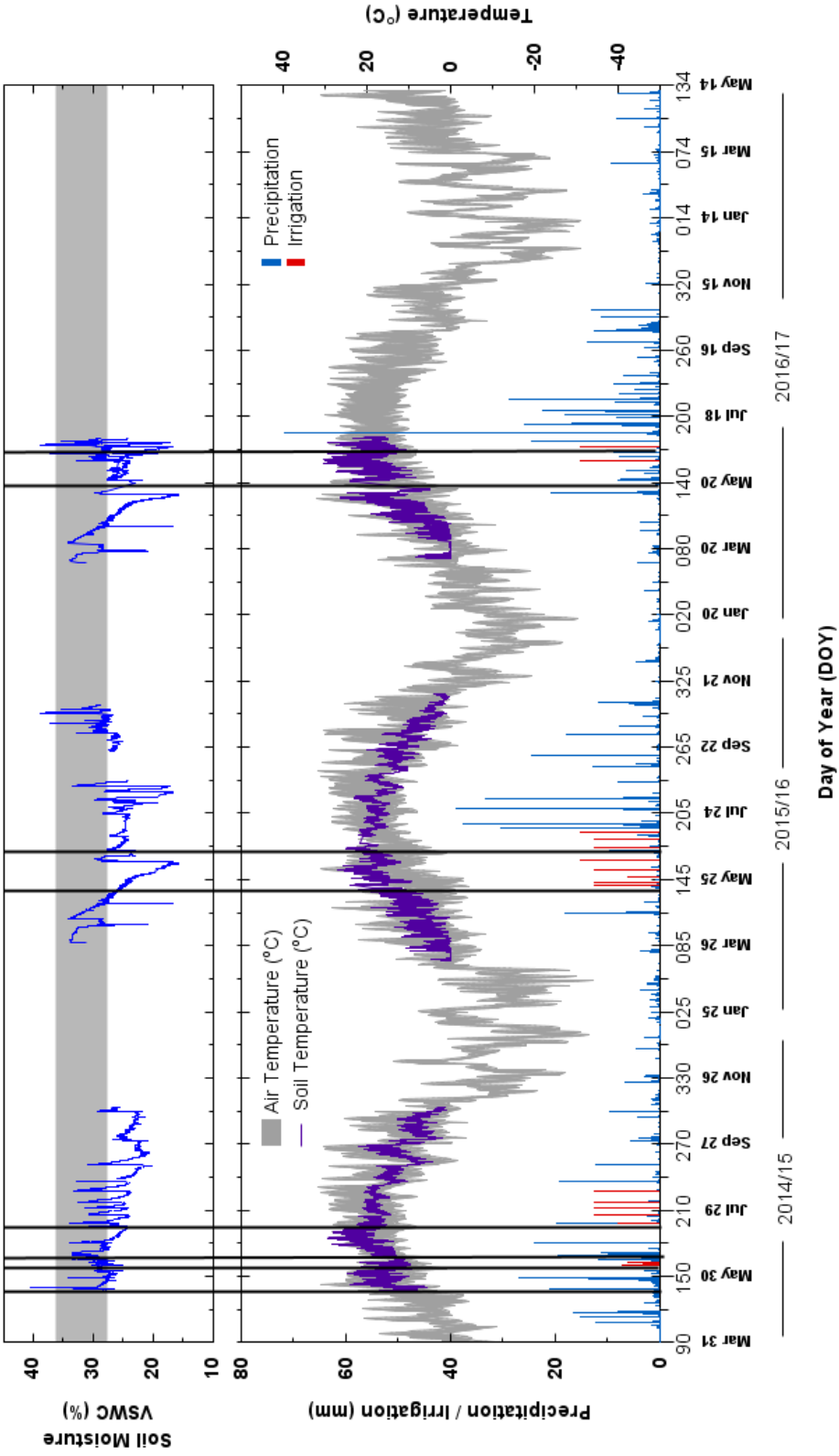
emission events. David et al. (2018) reported a similar result in irrigated systems on the prairies. The May–June emissions from PY2 were similar to the same period in PY3, but the percentage of the total is much higher because the emissions for the remainder of the year and following spring were extremely low, but spring emissions in PY3 were very high in comparison. These types of emission event are common for N<sub>2</sub>O emissions, and a large proportion of total N<sub>2</sub>O emissions can occur over a short time in response to management practices or climatic events (Venterea et al., 2012). Although PY3 had the most precipitation of any study year, the total cumulative emissions were similar to PY2. The growing season emissions were comparable, but the spring emission events were much larger in PY3, similar to the values from the spring of PY1. This may have been caused by a large amount of precipitation in October 2016 that may have kept the soil WFPS high until the soil froze, contributing to conditions that favour denitrification that led to high emissions in the spring. Early season precipitation in spring of PY3 was not above average, so it is likely that moisture from the fall was contained while frozen and contributed to the high emissions in the spring.

In addition to N<sub>2</sub>O, CO<sub>2</sub> fluxes were measured throughout the study to provide an indication of soil respiration (i.e., root and microbe) (van Veen et al., 1991; Xu et al., 2008). The N fertilizer treatments did not affect CO<sub>2</sub> emission, although correlations with N<sub>2</sub>O were weak to moderate for many treatments, with r values ranging from 0.25-0.70 (Appendix Table F.1). Microbial activity impacts CO<sub>2</sub> and N<sub>2</sub>O, and the correlation between these two greenhouse gases has been reported in other studies at site level as well as ecosystem level (Zou et al., 2004; Xu et al., 2008). Emissions of CO<sub>2</sub> were very low in the spring compared to the growing season and compared to N<sub>2</sub>O emissions during this time (Appendix F.2). This was likely due to the cold temperatures limiting microbial activity, as the soil moisture would have been high. Cumulative

CO<sub>2</sub> emissions in PY2 were significantly lower than other years ( $P = 0.001$ ), which suggests a lower level of microbial activity. Microbial activity may have been impacted by the lower soil moisture, which also influenced placement; N<sub>2</sub>O emissions from SB and BCI-O treatments were not significantly different at either rate in PY2.

The average seasonal water requirement for canola in Saskatchewan is 480 mm (Kruger, 2014). The total irrigation applied was 92.5 mm in 2014, 98.5 mm in 2015, and 30 mm in 2016. The amount of irrigation required for a crop depends on the amount of precipitation the site received. Very little additional moisture was required in 2016 because precipitation was higher than the 30-year average, so the site was only irrigated twice (Fig. 5.1). Large nitrous oxide fluxes are produced primarily by denitrification when water-filled pore space is above 60% (Davidson, 1991). The WFPS in this study was generally above 60% in the spring and early growing season and followed a general downward trend over the growing season, with peaks after substantial rainfall or irrigation events (Fig. 5.1).

Fertilizer guidelines for irrigated canola in Saskatchewan recommend N fertilizer rates of 160 to 180 kg N ha<sup>-1</sup> (ICDC, 2014, 2015, 2016). The recommended rates for this study, based on soil tests, were 121 kg N ha<sup>-1</sup> in 2014, 175 kg N ha<sup>-1</sup> in 2015, and 189 kg N ha<sup>-1</sup> in 2016. It is recognized that yield and protein content of canola generally increase with an increase in the amount of fertilizer N applied, but that the oil content generally decreases with increasing N application (Allen and Morgan, 1972; Bhatta, 1964; Henry and McDonald, 1978; Nuttall et al., 1987; Tomasiewicz, 2017). The yield response to N in this study was not significant in two out of three years and was very small in the other year, primarily due to large amounts of subsoil NO<sub>3</sub>-N. No real yield benefit was seen from higher N rates, but there was also no yield penalty



**Figure 5.1.** Climate data for the field site at Outlook PRFA station over three years of study. The bottom panel shows daily precipitation and irrigation, and the range of daily air temperature in the shaded area, with the purple lines showing soil temperature (0-5 cm). The top panel shows the soil moisture as volumetric soil water content (VSWC); the grey box represents WFPS at 60% for a range of bulk densities that have been recorded at the site. Above this level, the soil is highly susceptible to N<sub>2</sub>O production. The black bars represent seeding and/or fertilizer applications. Note: (i) In 2014 two additional seedings were required, (ii) soil moisture and temperature data were available only until June 2016 when the monitoring system was damaged by lightning.



for the lower N rates. Other researchers have concluded that N<sub>2</sub>O emissions could be reduced with no yield penalty by reducing the N applied to only what the crop requires (Engel et al., 2010; McSwiney and Robertson, 2005). The fields used in this study had been used for other research studies, thus, to reduce the impact of the previous crop, the canola was always preceded by unfertilized wheat. However, the lack of treatment effect on yield suggests the crop may have been able to access additional nitrogen from the soil. For example, in 2014, soil tests showed there was 245 kg N ha<sup>-1</sup> in the 30–60 cm depth—likely the reason for the lack of yield difference in this year—however in 2015 and 2016, the N available at this depth was 40 and 37 kg N ha<sup>-1</sup>, respectively.

Canola yield depends on many factors, including soil fertility, moisture availability and climatic conditions, and variety—with hybrid varieties often having a higher yield potential (Smith et al., 2010). The ten-year average (2006–2016) canola yield from Saskatchewan was 1835 kg ha<sup>-1</sup> (32.7 bu ac<sup>-1</sup>) and 1809 kg ha<sup>-1</sup> (32.3 bu ac<sup>-1</sup>) from the Rural Municipality (R.M. of Rudy no. 284) where the study site was located (Canola Council of Canada, 2017b; Government of Saskatchewan, 2018). This data does not specify if yields are from irrigated or dryland cropping, but likely includes both types of cropping systems. Data from Alberta shows the average canola yield from 2014–2016 for dryland was 2298 kg ha<sup>-1</sup> (41 bu ac<sup>-1</sup>) and for irrigated canola it was 3157 kg ha<sup>-1</sup> (56 bu ac<sup>-1</sup>), an increase of 37% (Agriculture Financial Services Corporation, 2015, 2016, 2017).

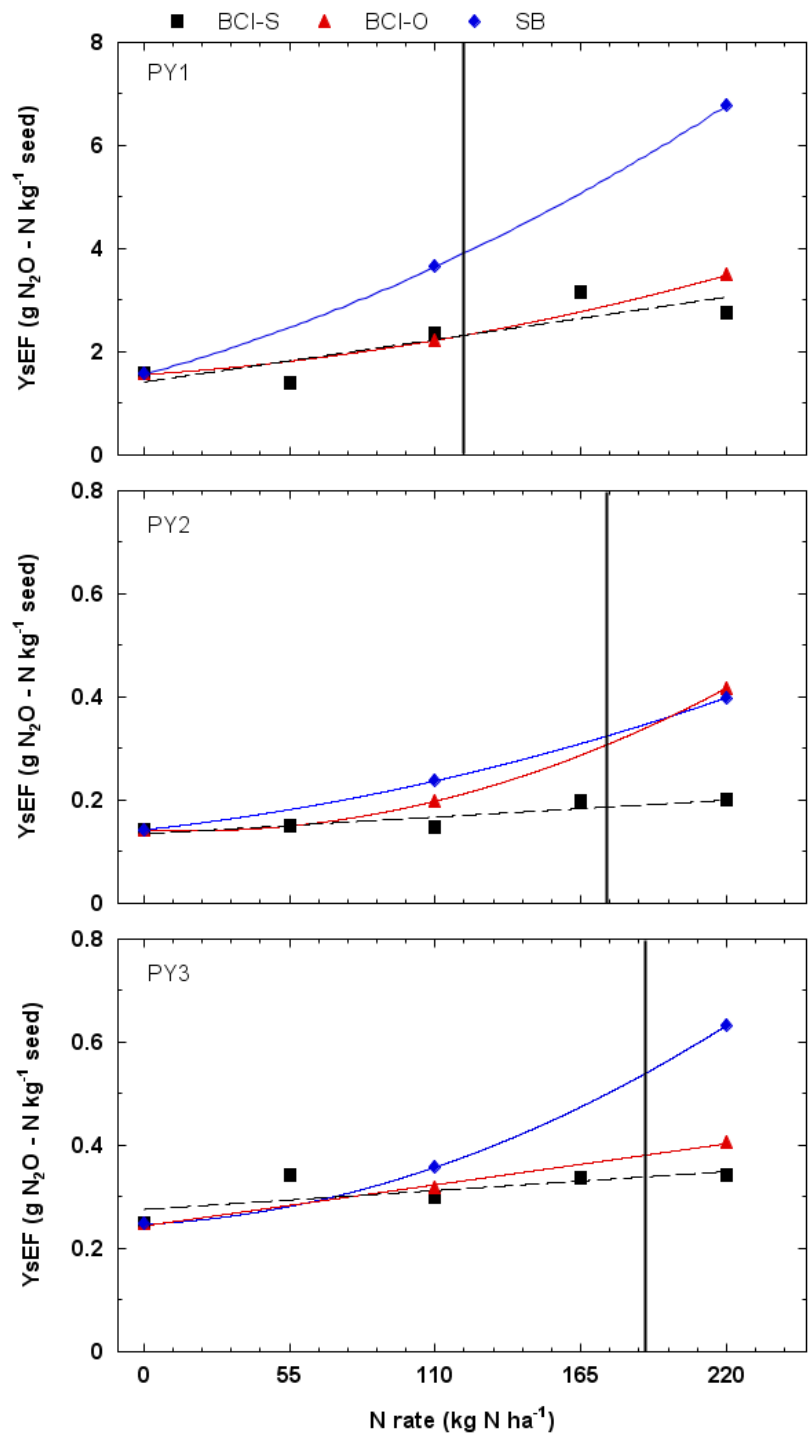
In 2014, the average canola yield was 2237 kg ha<sup>-1</sup> (39.9 bu ac<sup>-1</sup>) when averaged across all treatments, which is poor for an irrigated crop. Canola yields in 2015 and 2016 improved to 3495 kg ha<sup>-1</sup> (62.4 bu ac<sup>-1</sup>) and 3668 kg ha<sup>-1</sup> (65.4 bu ac<sup>-1</sup>) respectively. A significant treatment effect on

yield occurred only in 2015, when the check plots were lower yielding than the treatments that received N fertilizer. Total N uptake by the canola crop was greater in 2016 than in either 2014 or 2015. Nitrogen uptake in the straw was much greater in 2014 than 2015, with the opposite being true for the seed. This indicates that the N went to vegetative growth that didn't translate into seed fill, likely due to the late establishment of the crop and frost damage that occurred in September and which may have prevented the seeds from filling. The lack of yield response in 2014, as well as the high N uptake from the unfertilized plots, was likely due a large amount of N deeper in the soil. In 2015 BCI-S 220 kg N ha<sup>-1</sup> had the highest N uptake, but uptake was only significantly greater than BCI-S 55 kg N ha<sup>-1</sup> and the check plots. Results were similar in 2016—BCI-S 220 kg N ha<sup>-1</sup> had the highest N uptake and it was significantly greater than BCI-O at both rates and the check, with the other treatments in between (Fig. 4.8). These results indicate that splitting the fertilizer over two applications may improve the N uptake in canola, although the significance was low.

To estimate the direct N<sub>2</sub>O emissions from synthetic N fertilizer applied to soil, the IPCC uses a default emission factor of 1% of N fertilizer applied. In Canada, a Tier II methodology was used to develop the Canadian National Inventory Report (CNIR). Developed by Rochette et al. (2008a), the Tier II methodology estimates N<sub>2</sub>O emissions on the eco-district scale and includes several other factors that influence N<sub>2</sub>O emissions, such as no-till management, irrigation, soil texture, and landscape position (David et al., 2018; Rochette et al., 2008b). For irrigated land, it is assumed that precipitation and irrigation is equal to evapotranspiration; thus, all irrigated land is assigned an emission factor of 1.7% (Rochette et al., 2008a, b). In this study, however, irrigation was applied only to reduce the moisture deficit, especially during critical growth periods, but not eliminate it. Recent research performed on the semi-arid prairies showed that emission factors for

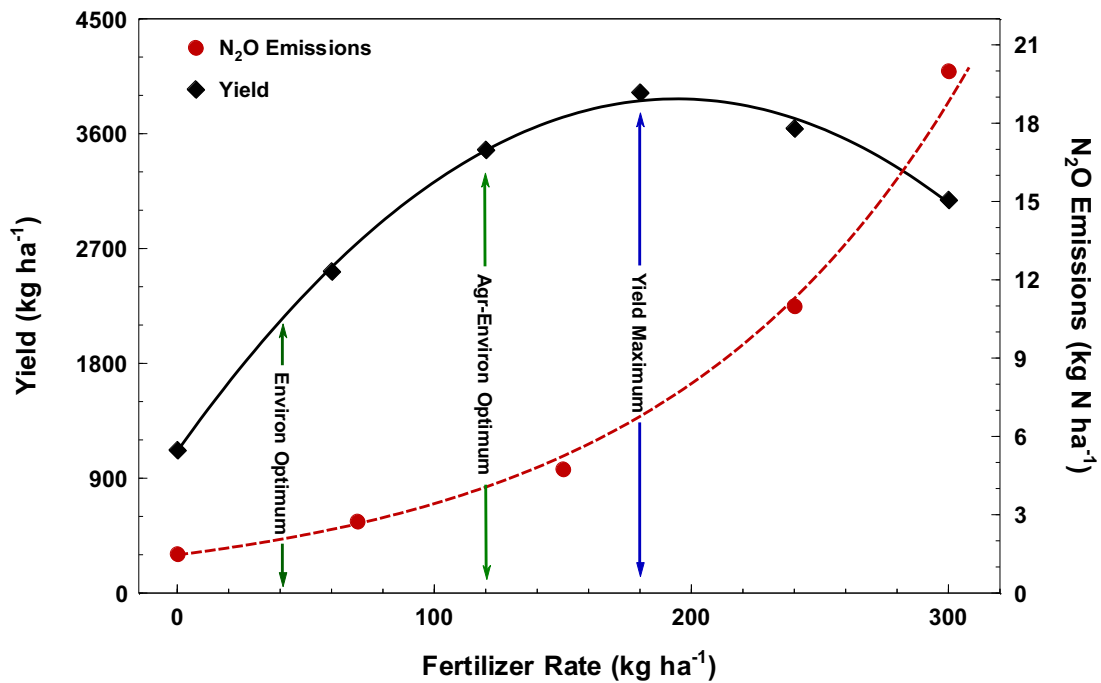
N<sub>2</sub>O are much lower than the IPCC values, and the EF used in the CNIR for irrigated cropping systems likely overestimates N<sub>2</sub>O emissions for this region (David et al., 2018). In a three-year study at several sites in Saskatchewan, Hultgreen and Leduc (2003) reported that the EF for broadcast urea and side-banded urea ranged from 0–0.5%, much lower than the IPCC estimate, but these values were likely impacted by the drought conditions that prevailed during much of the study. McSwiney and Robertson (2005) found emission factors in a study on maize in Michigan to be higher than the IPCC value, with a range of 2–7%. The variation in emission factors found by various researchers indicates that a standard emission factor is likely not an accurate way to calculate emissions from agriculture in geographically large countries like Canada, where there are significant variations in climate, soil type, and growing conditions. The Tier II methodology offers a more accurate picture because it accounts for several factors that affect emissions, but the single emission factor used for irrigated land may still be too high for use in the semi-arid prairie region of Western Canada.

The low yields in 2014 likely resulted from multiple issues mentioned previously. Due to the lack of establishment of the crop after seeding, the N application was not synchronized with the crop, and therefore N was available for microbial transformation to N<sub>2</sub>O. This was reflected in the extremely high emissions that occurred that were much greater than the following two years of the study. The combination of high emissions and low yields resulted in very high YsEFs compared to the other years. Figure 5.2 shows the impact on the YsEF by treatment and N rate; the YsEF for the side-banded treatments were higher than BCI-S and BCI-O in PY1 and PY2 and increased exponentially at the highest N rate. The optimum rate of fertilizer differs depending on perspective. The agronomic optimum rate of N fertilizer can be described as the rate that results in



**Figure 5.2.** Yield-scaled emission factor (YsEF) for each treatment and N rate. The vertical line represents the recommended fertilizer rate based on soil tests for that year.

the yield with the maximum economic return, whereas the environmental optimum rate of N fertilizer can be defined as the rate that produces the least amount of N<sub>2</sub>O emissions. By combining these two yield metrics yields the *agri-environmental optimum N rate*, which can be defined as the N rate that provides the greatest yield increase with the lowest FIE (i.e., the rate at which the YsEF is at a minimum). Theoretically, yield response to fertilizer N increases rapidly then slows, reaches a plateau, and declines. On the other hand, in response to increasing N rates, the N<sub>2</sub>O emission response curve increases in a slow, near-linear fashion at low to intermediate application rates (i.e., fertilizer N < crop requirement), but then increases rapidly (exponentially) as the application rate exceeds crop requirements (Fig. 5.3) (Johnson et al., 2012; McSwiney and Robertson, 2005).



**Figure 5.3.** A conceptual model of the effect of N fertilizer rate on yield and N<sub>2</sub>O emissions illustrating (i) the different optimum levels for environmental and yield targets, and (ii) the agri-environmental optimum.

In the present study, based on the cumulative N<sub>2</sub>O emissions and lack of yield response to higher N rates, the agri-environmental optimum fertilizer rate would be between 55 and 110 kg N ha<sup>-1</sup>. It is unlikely, however, that a producer would opt to apply the lowest N rate; consequently, a more practical recommendation would be between 90 and 110 kg N ha<sup>-1</sup>. The YsEFs at the 110 kg N ha<sup>-1</sup> rate were relatively independent of fertilizer management (i.e., placement or timing), but increased at 220 kg N ha<sup>-1</sup> and, in two out of three years, the greatest increases occurred when the fertilizer was side-banded (Fig. 5.2). Regarding application, this study found that N<sub>2</sub>O emissions were not affected by application type at rates close to the agri-environmental optimum. At rates above this, splitting the fertilizer (BCI-S) was the best option, followed by a one-time broadcast and incorporated (BCI-O). Side-banding was the least effective method for managing N<sub>2</sub>O emissions in this study.

## **6. SUMMARY AND CONCLUSIONS**

Agricultural activities contribute approximately 77% of the N<sub>2</sub>O emissions produced annually in Canada (Environment and Climate Change Canada, 2018). This is primarily due to the increased use of synthetic nitrogen fertilizer to maximize crop yields. The current challenge for the agricultural industry is to increase food production and reduce environmental impacts such as GHG emissions while doing so. An integral part of achieving this goal is better management of fertilizers in agricultural systems. In response to this challenge, the fertilizer industry and the scientific community developed 4R nutrient stewardship to promote the best management practices for nutrient use.

### **6.1 Summary of findings**

This study focused on GHG emissions from soil, specifically, N<sub>2</sub>O emissions caused by the application of nitrogen fertilizer. Emissions were measured over a production season of an irrigated canola crop for three years, i.e. from seeding to freeze-up and the following spring, to determine the effect of 4R nutrient management practices on emissions. A comparison of standard manually sampled flux measurement chambers, which has a low temporal density, with automated chambers interfaced to an FTIR gas analyzer for high frequency, real-time GHG measurements, was conducted to evaluate the effect of sampling frequency on cumulative GHG emission estimates. The results demonstrated that with strategic sampling (i.e. more frequent sampling during high flux periods, less frequent sampling during low flux periods) manual sampling

captures an accurate calculation of the cumulative emissions. The automated system captures very detailed information about emissions—useful for process-level studies.

Differences in the amount and timing of precipitation, and therefore soil moisture, over the three-year study, had a strong influence on N<sub>2</sub>O emissions. In PY2, there was much lower than normal precipitation around the time of fertilizer application which resulted in different emission patterns than PY1 and PY3, which had above-average precipitation during this time. A deep snowpack in early spring of 2014 also likely contributed to high soil moisture early in the growing season that contributed to establishment problems with the crop, and greater than average precipitation before the soil froze in 2015 may have led to much higher spring emissions in 2016 relative to the growing season.

The effect of nitrogen rate, timing, and placement on N<sub>2</sub>O emissions was studied using granular urea as the fertilizer source. Chapter 4 discussed how nitrogen rate affected N<sub>2</sub>O emissions with split fertilizer treatments (BCI-S) at rates of 55, 110, 165, and 220 kg N ha<sup>-1</sup>, where half of the total fertilizer rate was applied at seeding, and the other half before bolting of the canola. With the split treatment, the initial amount of fertilizer applied was less than the recommended fertilizer rates based on soil tests. The crop could use the N from the first fertilizer application during emergence and early growth, and when the top dress was applied the crop was in a rapid growth stage and could likely take up most of the top dress N, reducing the excess N available in the soil. Nitrous oxide emissions increased at total N rates of 165 and 220 kg N ha<sup>-1</sup>, whereas the 55 kg N ha<sup>-1</sup> rate consistently had emissions similar to the check plots (0 N).

To observe how the timing of fertilizer affected N<sub>2</sub>O emissions, a one-time broadcast and incorporated fertilizer application (BCI-O) was compared to the split application (BCI-S). At the



high rate of 220 kg N ha<sup>-1</sup>, splitting the fertilizer reduced N<sub>2</sub>O emissions compared to BCI-O in two of three years, but emissions were not reduced at the 110 kg N ha<sup>-1</sup> rate in any year. As discussed, this is likely because only half of the total amount was applied during each application, which was readily taken up by the canola crop.

The fertilizer placements compared were broadcast and incorporated (BCI-O) and side-banded (SB) urea. The results from these treatments were variable; e.g. the SB treatment yielded greater emissions than BCI-O in PY1 and PY3, while placement did not affect emissions in PY2. In general, side-banding the urea resulted in larger N<sub>2</sub>O-N losses when the soil moisture was high at the time of fertilizer application. As was seen with the timing treatments, a significant difference in emissions between the broadcast and side-banded occurred only at the high fertilizer rate (220 kg N ha<sup>-1</sup>). The likely reason for this is that the canola was able to take up the fertilizer at 110 kg N ha<sup>-1</sup>, regardless of placement. At 220 kg N ha<sup>-1</sup> there would have been excess N in the soil, and because banding the fertilizer can provide N for longer than broadcast treatments (Yan et al., 2001), the period of N<sub>2</sub>O flux from the SB treatment lasted longer than the BCI-O treatment. Typically, banding fertilizer is thought to be an effective mitigation strategy for N<sub>2</sub>O emissions, however, many researchers have also found inconsistent results from banding in terms of N<sub>2</sub>O reduction (Burton et al., 2008a; Engel et al., 2010; Hultgreen and Leduc, 2003).

There was no impact on yield from any of the N treatments, apart from the check plots having a lower yield than the N treatments (significant only in 2015). This may reflect the high concentration of nitrate deep in the soil that the crop may have been able to access. Overall, yields were good for irrigated canola, except in 2014, which had a poor yield due to several compounding factors. Due to the lack of treatment effect on yield, the yield-scaled emission factors (YsEF) were

highest from the high rate of fertilizer with all other N treatments not significantly greater than the check.

In this study I found the agri-environmental optimum N rate to be between 90 and 110 kg N ha<sup>-1</sup>. This is much lower than what the recommended N rate would typically be for an irrigated canola crop, and the rates recommended for the fields in this study (121–189 kg N ha<sup>-1</sup>). However, it has been suggested that nitrogen fertilizer rates could be reduced to only what the crop requires, and there would be no yield penalty (Engel et al., 2010; McSwiney and Robertson, 2005).

## **6.2 Conclusions**

The results from this three-year study found that 4R nutrient stewardship protocols can be effective at reducing N<sub>2</sub>O emissions under some conditions, such as when the rate of fertilizer applied is greater than what the crop requires. Under typical conditions and fertilizer rates, N<sub>2</sub>O emission factors in this region are relatively low compared to the IPCC emission factor. For irrigated cropping systems, the CNIR emission factor likely overestimates N<sub>2</sub>O emissions in this region. This study found that emissions were significantly reduced (i) by applying lower N rates, (ii) when the fertilizer was split over two applications to meet crop demand more effectively, and (iii) when the fertilizer was broadcast and incorporated instead of side-banded if the fertilizer rate is high (220 kg N ha<sup>-1</sup>).

## **6.3 Future research**

As illustrated during this three-year study, greenhouse gas emissions can be extremely variable year to year, which is why multi-year studies are necessary to obtain an accurate picture of emissions in the semi-arid prairies under various climatic conditions. There is great potential to

increase irrigated agriculture in Saskatchewan so determining the effect of irrigation on N<sub>2</sub>O emissions in this region and understanding the multitude of factors and interactions that contribute to GHG emissions is an important area for continued research.

This study looked at 4R nutrient stewardship principles separately, but producers would likely have an implementation strategy that would include a combination of 4R principles, so studies observing the effect of this on N<sub>2</sub>O and other GHG emissions could provide more insight to the best management practices. An example of this could be including enhanced efficiency N fertilizers that include nitrification inhibitors, urease inhibitors, or a combination of both, and coatings that slow the release of nitrogen (Akiyama et al., 2010; Halvorson and Del Grosso, 2013). The use of enhanced efficiency fertilizers in combination with the 4R principles discussed here could synchronize N with crop demands in a way that could reduce labour for producers while also reducing N<sub>2</sub>O emissions. Technological advances also have been made in variable rate technology, where fields can be mapped precisely to match patterns of crop productivity and then place higher or lower rates of fertilizer to areas depending on the yield potential (Robertson and Vitousek, 2009). Nitrogen availability in a field is variable due to the inherent heterogeneity of soil and geomorphic features, so fertilization strategies that aim only to maximize yield can lead to substantial over-fertilization of naturally low yielding areas (Robertson and Vitousek, 2009). Variable rate fertilization could be an effective way to reduce the amount of excess N applied in places where yield potentials are inherently lower. Another avenue of future research could be incorporating 4R management with different crop rotations and cover crops, especially leguminous crops that fix N<sub>2</sub>, which can reduce the N fertilizer requirement for subsequent crops.

## REFERENCES

- Agriculture and Agri-Food Canada. 2014. Moisture deficits in the prairie region. Available at <http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/agriculture-and-climate/future-outlook/climate-change-scenarios/moisture-deficits-in-the-prairie-region/?id=1363104397771> (verified 13 July 2018).
- Agriculture and Agri-Food Canada. 2015. Impact of climate change on Canadian agriculture. Available at <http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/agriculture-and-climate/future-outlook/impact-of-climate-change-on-canadian-agriculture/?id=1329321987305> (verified 17 May 2018).
- Agriculture and Agri-Food Canada. 2016. Canada-Saskatchewan Irrigation Diversification Centre Research and Demonstrations. Available at <http://www.agr.gc.ca/eng/about-us/offices-and-locations/canada-saskatchewan-irrigation-diversification-centre/canada-saskatchewan-irrigation-diversification-centre-research-and-demonstrations/?id=1186154519158> (verified 24 May 2018).
- Agriculture Financial Services Corporation. 2015. Yield Alberta 2015. Available at <https://www.afsc.ca/doc.aspx?id=7883> (verified 31 October 2018).
- Agriculture Financial Services Corporation. 2016. Yield Alberta 2016. Available at <https://www.afsc.ca/doc.aspx?id=8065> (verified 31 October 2018).
- Agriculture Financial Services Corporation. 2017. Yield Alberta 2017. Available at [https://www.agcanada.com/digital-edition/yield-alberta\\_2017-02-27/](https://www.agcanada.com/digital-edition/yield-alberta_2017-02-27/) (verified 31 October 2018).
- Akiyama, H., X. Yan, and K. Yagi. 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N<sub>2</sub>O and NO emissions from agricultural soils: meta-analysis. *Global Change Biol.* 16: 1837–1846.
- Allen, D.E., G. Kingston, H. Rennenberg, R.C. Dalal, and S. Schmidt. 2010. Effect of nitrogen fertilizer management and waterlogging on nitrous oxide emission from subtropical sugarcane soils. *Agric. Ecosyst. Environ.* 136: 209–217.

- Allen, E.J. and D.G. Morgan. 1972. A quantitative analysis of the effect of nitrogen on the growth, development and yield of oilseed rape. *J. Agric. Sci.* 78:315–24.
- Amadi, C. 2016. Dynamics of carbon dioxide, methane and nitrous oxide fluxes in planted shelterbelts and adjacent cropped fields. PhD thesis. University of Saskatchewan. Saskatoon, SK.
- Babock, B.A. 1992. The effects of uncertainty on optimal nitrogen applications. *Rev. Agr. Econ.* 14: 271–80.
- Bhatty, R. S. 1964. Influence of nitrogen fertilization on the yield, protein, and oil content of two varieties of rape. *Can. J. Plant Sci.* 44: 215–217.
- Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes. 2002. Emissions of N<sub>2</sub>O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochem. Cy.* 16. doi:10.1029/2001GB001811.
- Bruulsema, T., J. Lemunyon, and B. Herz. 2009. Know your fertilizer rights. *Crops Soils* 42: 13-18.
- Burton, D.L., X. Li, and C.A. Grant. 2008a. Influence of fertilizer nitrogen source and management practice on N<sub>2</sub>O emissions from two Black Chernozemic soils. *Can. J. Soil Sci.* 88: 219-227.
- Burton, D.L., B.J. Zebarth, K.M. Gillam, J.A. MacLeod. 2008b. Effect of split application of fertilizer nitrogen on N<sub>2</sub>O emissions from potatoes. *Can. J. Soil Sci.* 88: 229–239.
- Butterbach-Bahl, K., E.M. Baggs, M. Dannenmann, R. Kiese, and S. Zechmeister-Boltenstern. 2013. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? *Phil. Trans. R. Soc. B.* 368: 20130122. doi:10.1098/rstb.2013.0122.
- Calderon, F.J., and L. Jackson. 2002. Rototillage, disking, and subsequent irrigation: Effects on soil nitrogen dynamics, microbial biomass, and carbon dioxide efflux. *J. Environ. Qual.* 31: 752–758.
- Canola Council of Canada, 2010. Estimated acreage and percentage of HT and conventional canola. Available at <https://www.canolacouncil.org/markets-stats/statistics/estimated-acreage-and-percentage/> (verified 17 July 2018).
- Canola Council of Canada, 2017a. Canola encyclopedia. Available at <https://www.canolacouncil.org/canola-encyclopedia/> (verified 26 July 2018).

- Canola Council of Canada. 2017b. Canadian canola yield; bushels per acre. Available at <https://www.canolacouncil.org/markets-stats/statistics/bushelsacre/> (verified 25 June 2018).
- Canola Council of Canada. 2017c. Sclerotinia stem rot. Available at <https://www.canolacouncil.org/canola-encyclopedia/diseases/sclerotinia-stem-rot/#disease-cycle> (verified 1 February 2018).
- Chantigny, M. H., D. Prévost, D.A. Angers, R.R. Simard, and F.P. Chalifour. 1998. Nitrous oxide production in soils cropped to corn with varying N fertilization. *Can. J. Soil Sci.* 78: 589-596.
- Chen, D., Y. Li, P. Grace, and A.R. Mosier. 2008. N<sub>2</sub>O Emissions from Agricultural Lands: A Synthesis of Simulation Approaches. *Plant and Soil* 309: 169–89. doi:10.1007/s11104-008-9634-0.
- Cheng, W., Y. Nakajima, S. Sudo, H. Akiyama, and H. Tsuruta. 2002. N<sub>2</sub>O and NO emissions from a field of Chinese cabbage as influenced by band application of urea or controlled-release urea fertilizers. *Nutr. Cycl. Agroecosys.* 63: 231–38.
- Cicerone, R.J. 1987. Changes in stratospheric ozone. *Science* 237: 35-42.
- Cole, C.V., J. Duxbury, J. Freney, O. Heinemeyer, K. Minami, A. Mosier, K. Paustian, N. Rosenberg, N. Sampson, D. Sauerbeck, Q. Zhao. 1997. Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutr. Cycl. Agroecosys.* 49: 221–28.
- Colwell, J.D. 1994. Estimating fertilizer requirements: A quantitative approach. CAB International, Wallingford.
- Cote, M. 2006. The Encyclopedia of Saskatchewan: Climate. Canadian Plains Research Centre. Available at <http://esask.uregina.ca/entry/climate.html> (verified 7 August 2017).
- Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: *Climate Change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

- Cutforth, H.W., S.V. Angadi, B.G. McConkey, P.R. Miller, D. Ulrich, R. Gulden, K.M. Volkmar, M.H. Entz, S.A. Brandt. 2013. Comparing rooting characteristics and soil water withdrawal patterns of wheat with alternative oilseed and pulse crops grown in the semiarid Canadian Prairie. *Can. J. Soil Sci.* 93:147–60.
- David, C. 2014. Greenhouse gas emissions from irrigated crop production in the Canadian Prairies. M.Sc. thesis, University of Saskatchewan, Saskatoon.
- David, C., R. Lemke, W. Helgason, and R.E. Farrell. 2018. Current inventory approach overestimates the effect of irrigated crop management on soil-derived greenhouse gas emissions in the semi-arid Canadian Prairies. *Agricultural Water Management* 208: 19–32.
- Davidson, E.A. 1991. Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. P. 219–235 in Rogers, J.E., Whitman, W.B. eds. *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes*. Washington (DC): American Society for Microbiology.
- Davidson, E.A., M. Keller, H.E. Erickson, L.V. Verchot, and E Veldkamp. 2000. Testing a conceptual model of soil emissions of nitrous and nitric oxides. *BioSci.* 50: 667-680. doi:10.1641/0006-3568(2000)050[0667:TACMOS]2.0.CO;2.
- Dobbie, K.E., I.P. McTaggart, and K.A. Smith. 1999. Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors. *J. Geophys. Res.* 104: 26891-26899.
- Dörsch, P., A. Palojarvi, and S. Mommertz. 2004. Overwinter Greenhouse Gas Fluxes in Two Contrasting Agricultural Habitats. *Nutrient Cycling in Agroecosystems* 70: 117–33. doi: 10.1023/B:FRES.0000048473.11362.63.
- Downey, R.K., A.J. Klassen, and J. McAnsh. 1974. Rapeseed: Canada's "Cinderella" crop. Publ. 33. Rapeseed Assoc. of Canada, Winnipeg, MB.
- Ehhalt, D., M. Prather, F. Dentener, R. Derwent, E. Dlugokencky, E. Holland, I. Isaksen, J. Katima, V. Kirchhoff, P. Matson, P. Midgley, M. Wang. 2001. Atmospheric chemistry and greenhouse gases. In: *Climate Change 2001: The scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

- Engel, R., D.L. Liang, R. Wallander, and A. Bembenek. 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. *J. Environ. Qual.* 39: 115–125. doi:10.2134/jeq2009.0130.
- Environment and Climate Change Canada. 2018. National inventory report executive summary: 1990-2016: Greenhouse gas sources and sinks in Canada. Available at <https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/emissions-inventories-reporting/nir-executive-summary/National%20Inventory%20Report%20Executive%20Summary%202018.pdf> (verified 10 September 2018).
- Environment Canada. 2016. National Inventory Report executive summary: 1990-2015: Greenhouse gas sources and sinks in Canada. Available at <https://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=662F9C56-1> (verified 3 August 2017).
- Environment Canada. 2015. Canadian Climate Normals 1981-2010 Station Data: Outlook, SK. Available at [http://climate.weather.gc.ca/climate\\_normals/results\\_1981\\_2010\\_e.html?stnID=3318&lang=e&StationName=outlook&SearchType=Contains&stnNameSubmit=go&dCode=4&dispBack=1](http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=3318&lang=e&StationName=outlook&SearchType=Contains&stnNameSubmit=go&dCode=4&dispBack=1) (verified 21 March 2016).
- Environment Canada. 2018. Historical climate data: Daily snow on the ground. Available at [http://climate.weather.gc.ca/climate\\_data/generate\\_chart\\_e.html?hlyRange=1996-08-26|2018-09-26&dlyRange=1952-05-01|2018-09-25&mlyRange=1952-01-01|2007-11-01&StationID=3318&Prov=SK&urlExtension=\\_e.html&searchType=stnName&optLimit=yearRange&StartYear=2013&EndYear=2018&selRowPerPage=25&Line=0&searchMethod=contains&Month=3&Day=1&txtStationName=Outlook&timeframe=2&Year=2014&type=bar&MeasTypeID=snow](http://climate.weather.gc.ca/climate_data/generate_chart_e.html?hlyRange=1996-08-26|2018-09-26&dlyRange=1952-05-01|2018-09-25&mlyRange=1952-01-01|2007-11-01&StationID=3318&Prov=SK&urlExtension=_e.html&searchType=stnName&optLimit=yearRange&StartYear=2013&EndYear=2018&selRowPerPage=25&Line=0&searchMethod=contains&Month=3&Day=1&txtStationName=Outlook&timeframe=2&Year=2014&type=bar&MeasTypeID=snow) (verified 11 October 2018).
- Farrell, R.E. and C.L. David. 2014. Greenhouse gas emissions and mitigation in irrigated cropping systems of the Northern Great Plains: A Western Canadian perspective. Saskatoon, SK. doi:10.13140/RG.2.2.14823.44965.
- Farrell, R.E. and J.A. Elliot. 2008. Soil Air, in: Carter, M.R. and Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*. 2nd Edition. CRC Press Taylor & Francis, Boca Raton, FL, Chapter 64.
- Firestone, M.K., and E.A. Davidson. 1989. Microbiological basis of NO and N<sub>2</sub>O production and consumption in soil. p. 7–21. In M.O. Andreae and D.S. Schimel (ed.) *Exchange of trace gases between terrestrial ecosystems and the atmosphere*. John Wiley & Sons, New York.
- Flynn H.C. and P. Smith. 2010. Greenhouse gas budgets of crop production –Current and likely future trends. Paris, France: International Fertilizer Industry Association (IFA). Available at <https://core.ac.uk/download/pdf/177244.pdf> (verified 3 May 2018).



- Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. van Dorland, 2007. Changes in atmospheric constituents and in radiative forcing. In: *Climate Change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change*. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Gan, Y., L. Liu, H. Cutforth, X. Wang, and G. Ford. 2011. Vertical distribution profiles and temporal growth patterns of roots in selected oilseeds, pulses and spring wheat. *Crop Pasture Sci.* 62: 457–66. doi: 10.1071/CP10406.
- Gan, Y., S.S. Malhi, S. Brandt, F. Katepa-Mupondwa, and C. Stevenson. 2008. Nitrogen use efficiency and nitrogen uptake of *juncea* canola under diverse environments. *Agron. J.* 100: 285–295. doi:10.2134/agronj2007.0229.
- Gao, X., S. Parsonage, M. Tenuta, K. Baron, K. Hanis-Gervais, A. Nelson, D. Tomasiewicz, and R. Mohr. 2017. Nitrogen fertilizer management practices to reduce N<sub>2</sub>O emissions from irrigated processing potato in Manitoba. *Am. J. Potato Res.* 94: 390–402.
- Government of Alberta. 2001. Soil moisture and temperature consideration. Available at [https://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/crop1272](https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop1272) (verified 13 July 018).
- Government of Alberta. 2016. Alberta irrigation scheduling manual. Available at [http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/irr14310/\\$file/2016\\_irr\\_manag\\_manual.pdf?OpenElement](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/irr14310/$file/2016_irr_manag_manual.pdf?OpenElement) (verified 27 March 2019).
- Government of Manitoba. 2009. Manure nutrients and their behaviour in soil. Available at [https://www.gov.mb.ca/agriculture/environment/nutrient-management/pubs/mmf\\_manurenutribehaviour\\_factsheet.pdf](https://www.gov.mb.ca/agriculture/environment/nutrient-management/pubs/mmf_manurenutribehaviour_factsheet.pdf) (verified 20 November 2018).
- Government of Saskatchewan. 2008. Irrigation Certification: Developing a prosperous and sustainable irrigation industry. Available at <http://publications.gov.sk.ca/documents/20/83765-88bd0590-0078-4796-bfad-aa653f3516fc.pdf> (verified 22 May 2018).
- Government of Saskatchewan. 2017a. Crop Planning Guide 2017. Available at <http://publications.gov.sk.ca/documents/20/97026Crop%20Plannig%20Guide%20Complete%20Version%2003-17.pdf> (verified 22 May 2018).

- Government of Saskatchewan. 2017b. Nitrogen fertilization in crop production. Available at <http://publications.gov.sk.ca/documents/20/84107-Nitrogen%20Fertilization%20in%20Crop%20Production%20-%202002-17.pdf> (verified 18 September 2017).
- Government of Saskatchewan. 2018. Crop yields by rural municipality. Available at <http://www.agriculture.gov.sk.ca/rmyields> (verified 25 June 2018).
- Grant, C.A. and L.D. Bailey. 1993. Fertility management in canola production. *Can. J. Plant Sci.* 73: 651–70.
- Grant, C.A., K.R. Brown, G.J. Racz, and L.D. Bailey. 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 :629–38.
- Grant, R.F., E. Pattey, T.W. Goddard, L.M. Kryzanowski, and H. Puurveen. 2006. Modeling the effects of fertilizer application rate on nitrous oxide emissions. *Soil Sci. Soc. Am. J.* 70: 235-248.
- Grant, B., W.N. Smith, R. Desjardins, R. Lemke, and C. Li. 2004. Estimated N<sub>2</sub>O and CO<sub>2</sub> emissions as influenced by agricultural practices in Canada. *Climatic Change* 65: 315–32.
- Halvorson, A.D., and S.J. Del Grosso. 2012. Nitrogen uource and placement effects on soil nitrous oxide emissions from no-till corn. *J. Environ. Qual.* 41: 1349–1360.
- Halvorson, A.D., and S.J. Del Grosso. 2013. Nitrogen placement and source effects on nitrous oxide emissions and yields of irrigated corn. *J. Environ. Qual.* 42: 312–322.
- Halvorson, A.D., S.J. Del Grosso, and C.A. Reule. 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. *J. Environ. Qual.* 37: 1337–44.
- Hao, X., C. Chang, J.M. Carefoot, H.H. Janzen, and B.H. Ellert. 2001. Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutr. Cycl. Agroecosys.* 60: 1–8.

- Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai. 2013. Observations: Atmosphere and surface. In: Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Henry, J.L. and K.B. McDonald. 1978. The effects of soil and fertilizer nitrogen and moisture stress on yield, oil and protein content of rape. *Can. J. Plant Sci.* 58: 303–310.
- Horton, R., G. L. Kluitenberg, and K. L. Bristow. 1994. Surface crop residue effects on the soil surface energy balance. In: P. W. Unger (Ed.) *Managing agricultural residues*, p. 143–162. Boca Raton, FL. Lewis Publishers, CRC Press.
- Hultgreen, G. and P. Leduc. 2003. The effect of nitrogen fertilizer placement, formulation, timing, and rate on greenhouse gas emissions and agronomic performance. Final Report, Project No. 5300G, ADF#19990028, Saskatchewan Department of Agriculture and Food, Regina, SK.
- Hutchinson, G.L., and A.R. Mosier. 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. *Soil Sci. Soc. Am. J.* 45: 311-316.
- Hutchinson, J. J. B.B. Grant, W.N. Smith, R.L. Desjardins, C.A. Campbell, D.E. Worth, X.P. Vergé. 2007. Estimates of direct nitrous oxide emissions from Canadian agroecosystems and their uncertainties. *Can. J. Soil Sci.* 87 :141–152.
- Irrigation Crop Diversification Corporation (ICDC). 2013. Crop rotations under irrigation. Irrigation Agronomy Workshop, 9 April 2013, Outlook, SK. Available at <http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2015/01/2013-Crop-Rotations-Under-Irrigation.pdf> (verified 29May 2018).
- Irrigation Crop Diversification Corporation (ICDC). 2014. Irrigation economics and agronomics. Available at [http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2014/10/2014\\_Agronomics\\_and\\_Economics.pdf](http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2014/10/2014_Agronomics_and_Economics.pdf)
- Irrigation Crop Diversification Corporation (ICDC). 2015. Irrigation economics and agronomics. Available at <http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2014/11/2015-Economics-Agronomics.pdf>

- Irrigation Crop Diversification Corporation (ICDC). 2016. Irrigation economics and agronomics. Available at [http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2016/01/2016\\_economics\\_agronomics.pdf](http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2016/01/2016_economics_agronomics.pdf)
- Irrigation Crop Diversification Corporation (ICDC). 2017. Irrigation economics and agronomics. Available at <http://irrigationsaskatchewan.com/icdc/wp-content/uploads/2017/03/2017-Economics-Agronomics.pdf> (verified 15 August 2017)
- International Plant Nutrition Institute (IPNI). 2015. 4R Plant Nutrition Manual: A manual for improving the management of plant nutrition, metric version (T.W. Bruulsema, P.E. Fixen, G.D. Sulewski, eds.). International Plant Nutrition Institute. Norcross, GA, USA.
- International Plant Nutrition Institute (IPNI). 2016. Nitrogen notes: 4. Nitrification. Available at [http://www.ipni.net/publication/nitrogen-en.nsf/book/7F7F448C4D064A5985257C13004C83A3/\\$FILE/NitrogenNotes-EN-04.pdf](http://www.ipni.net/publication/nitrogen-en.nsf/book/7F7F448C4D064A5985257C13004C83A3/$FILE/NitrogenNotes-EN-04.pdf) (verified 6 April 2016).
- Izaurrealde, R.C., R.L. Lemke, T.W. Goddard, B.G. McConkey, and Z. Zhang. 2004. Nitrous oxide emissions from agricultural toposequences in Alberta and Saskatchewan. *Soil Sci. Soc. Am. J.* 68:1285–94.
- Johnson, J.M.F., S.L. Weyers, D.W. Archer, and N.W. Barbour. 2012. Nitrous oxide, methane emission, and yield-scaled emission from organically and conventionally managed systems. *Soil Sci. Soc. Am. J.* 76: 1347.
- Johnston, A.M. D.L. Tanaka, P.R. Miller, S.A. Brandt, D.C. Nielsen, G.P. Lafond, N.R. Riveland. 2002. Oilseed Crops for Semiarid Cropping Systems in the Northern Great Plains. *Agron. J.* 94: 231–40.
- Kachanoski, R. G. 2009. Crop response to nitrogen fertilizer: The delta yield concept. *Can. J. Soil Sci.* 89: 543–54.
- Kessavalou, A., J.W. Doran, A.R. Mosier, and R.A. Drijber. 1998. Greenhouse gas fluxes following tillage and wetting in a wheat-fallow cropping system. *J. Environ. Qual.* 27 :1105.
- Krogman, K.K. and E.H. Hobbs. 1975. Yield and morphological response of rape (*Brassica campestris* L. cv. Span) to irrigation and fertilizer treatments. *Can. J. Plant Sci.* 55: 903–909.
- Kruger, G. 2014. High yielding canola irrigation. Available at <http://www.irrigationsaskatchewan.com/icdc/wp-content/uploads/2015/01/2014-AU-Gary-Kruger-High-Yielding-Canola-Irrigation.pdf> (verified 22 June 2018).
- Lal, R. 1991. Tillage and agricultural sustainability. *Soil Tillage Res.* 20: 133–46.

- Lal, R. and J. M. Kimble. 1997. Conservation tillage for carbon sequestration. *Nutr. Cycl. Agroecosys.* 49: 243–53.
- Lascano, R. J. and R. L. Baumhardt. 1996. Effects of crop residue on soil and plant water evaporation in a dryland cotton system. *Theor. Appl. Climatol.* 54: 69–84.
- Lemke, R., R.C. Izaurralde, S.S. Malhi, M.A. Arshad, and M. Nyborg. 1998. Nitrous oxide emissions from agricultural soils of the Boreal and Parkland Regions of Alberta. *Soil Sci. Soc. Am. J.* 62: 1096–1102. doi:10.2136/sssaj1998.03615995006200040034x.
- Lemke, R., R.C. Izaurralde, M. Nyborg, and E.D. Solberg. 1999. Tillage and N source influence soil-emitted nitrous oxide in the Alberta Parkland Region. *Can. J. Soil Sci.* 79: 15–24.
- Lemke, R., H.H. Janzen, and P. Rochette. 1999. Processes of N<sub>2</sub>O emissions from Canadian agroecosystems. In R. L. Desjardins, J. C. Keng, and K. Haugen-Kozyra, eds. *Reducing nitrous oxide emissions from agroecosystems. Proceedings of an International N<sub>2</sub>O Workshop, Banff, AB. 1999 Mar. 03-05.*
- Le Mer, J. and P. Roger. 2001. Production, oxidation, emission and consumption of methane by soils: A review. *Eur. J. Soil Biol.* 37: 25–50. doi:10.1016/S1164-5563(01)01067-6.
- Liebig, M.A., J.A. Morgan, J.D. Reeder, B.H. Ellert, H.T. Gollany, G.E. Schuman. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil Tillage Res.* 83: 25-52. doi:10.1016/j.still.2005.02.008.
- Linn, D.M. and J.W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. *Soil Sci. Soc. Am. J.* 48: 1267-1272.
- Malhi, S.S., C.A. Grant, A.M. Johnston, and K.S. Gill. 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., R. Lemke, Z.H. Wang, and B.S. Chhabra. 2006. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality and greenhouse gas emissions. *Soil Til. Res.* 90: 171-183.
- Manning, S.L.R. 1988. A socio-economic analysis of adoption of irrigation in Saskatchewan. MSc. Thesis. University of Saskatchewan, Saskatoon.
- Marland, G., T.O. West, B. Schlamadinger, and L. Canella. 2003. Managing soil organic carbon in agriculture: the net effect on greenhouse gas emissions. *Tellus B Chem. Phys. Meteorol.* 55: 613-621.

- Maynard, D.G., Y.P. Kalra, J.A. Crumbaugh. 2008. Nitrate and exchangeable ammonium nitrogen, in Carter, M.R. and Gregorich, E.G. (Eds.), *Soil Sampling and Methods of Analysis*. 2nd Edition. CRC Press Taylor & Francis, Boca Raton, FL, Chapter 6.
- McSwiney, C. P. and G. P. Robertson. 2005. Nonlinear response of N<sub>2</sub>O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. *Global Change Biol.* 11: 1712–1719. doi:10.1111/j.1365-2486.2005.01040.x.
- Metwally T.F., E.E. Gewaily, and S.S. Naeem. 2011. Nitrogen response curve and nitrogen use efficiency of Egyptian hybrid rice. *J. Agric. Res. Kafer El Sheikh Univ.* 37: 73–84.
- Mosier, A.R. 1989. Chamber and isotope techniques. p. 175-188. In: Andreae, M.O., and Schimel, D.S. *eds.*, *Exchange of trace gases between terrestrial ecosystems and the atmosphere*. John Wiley and Sons, NY.
- Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. *J. Environ. Qual.* 35: 1584-1598.
- Müller, C., M. Martin, R.J. Stevens, R.J. Laughlin, C. Kammann, J.C.G. Ottow, H.-J. Jäger. 2002. Processes leading to N<sub>2</sub>O emissions in grassland soil during freezing and thawing. *Soil Biol. Biochem.* 34: 1325–31.
- Mussell, A., C. Schmidt, and D. Heaney. 2014. Sustainably increasing crop production in Alberta: land use, nutrient management, greenhouse gas emissions, and economics. RandomCross Consulting.
- Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang. 2013. Anthropogenic and Natural Radiative Forcing. In: *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Nash, P.R., P.P. Motavalli, and K.A. Nelson. 2012. Nitrous oxide emissions from claypan soils due to nitrogen fertilizer source and tillage/fertilizer placement practices. *Soil Sci. Soc. Am. J.* 76: 983-993.
- Nuttall, W., H. Ukrainetz, J.W.B. Stewart, and D.T. Spurr. 1987. The effect of nitrogen, sulphur and boron on yield and quality of rapeseed (*Brassica napus* L. and *B. Campestris* L.). *Can. J. Soil Sci.* 67: 545–559.

- Nyborg, M, J.W. Laidlaw, E.D. Solberg, and S.S. Malhi. 1997. Denitrification and nitrous oxide emissions from a Black Chernozemic soil during spring thaw in Alberta. *Can. J. Soil Sci.* 77: 153-160.
- Oertel, C., J. Matschullat, K. Zurba, F. Zimmermann, and S. Erasmi. 2016. Greenhouse gas emissions from soils - A review. *Chemie Der Erde – Geochem.* 76: 327–52.
- Padbury, G., S. Waltman, J. Caprio, G. Coen, S. McGinn, D. Mortensen, G. Nielsen, and R. Sinclair. 2002. Agroecosystems and land resources of the northern Great Plains. *Agron. J.* 94: 251–261.
- Paterson Earth & Water Consulting. 2015. Economic Value of Irrigation in Alberta. Prepared for the Alberta Irrigation Projects Association. Lethbridge, Alberta, Canada.
- Pederson, A.R. 2017. HMR: Flux estimation with static chamber data. Available at <https://cran.r-project.org/web/packages/HMR/HMR.pdf> (verified on 14 September 2017).
- Pedersen, A.R., S.O. Petersen, and K. Schelde. 2010. A comprehensive approach to soil atmosphere trace-gas flux estimation with static chambers. *Eur. J. Soil Sci.* 61: 888-902.
- Pennock, D. J., T.T. Yates, and J.T. Braidek. 2006. Towards optimum sampling for regional-scale N<sub>2</sub>O emission monitoring in Canada. *Can. J. Soil Sci.* 86: 441–50.
- Portmann, R.W., J.S. Daniel, and A.R. Ravishankara. 2012. Stratospheric ozone depletion due to nitrous oxide: Influences of other gases. *Phil. Trans. R. Soc. B.* 367:1256–64.
- Ribaudo, M., L. Hansen, M. Livingston, R. Mosheim, J. Williamson, J. Delgado. 2011. Nitrogen in agricultural systems: Implications for conservation policy. USDA- ERS Economic Research Report.
- Roberts, T.L. 2007. Right product, right rate, right time and right place ... the foundation of best management practices for fertilizer. *Fertilizer Best Management Practices. General Principles, Strategy for their Adoption, and Voluntary Initiatives vs. Regulations.* Proc. of IFA International Workshop, 7–9 March 2007, Brussels, Belgium, International Fertilizer Industry Association, Paris, France. 29-32.
- Roberts, W.P. and P.R. Chan. 1990. Tillage-induced increases in carbon dioxide loss from soil. *Soil Tillage Res.* 17: 143-151.
- Robertson G.P. and P.M. Vitousek. 2009. Nitrogen in agriculture: balancing the cost of an essential resource. *Annu. Rev. Environ. Resour.* 34: 97-125.

- Rochette, P., D.E. Worth, E.C. Huffman, J.A. Brierley, B.G. McConkey, J. Yang, J.J. Hutchinson, R.L. Desjardins, R. Lemke, and S. Gameda. 2008a. Estimation of N<sub>2</sub>O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. *Can. J. Soil Sci.* 88: 655–69.
- Rochette, P., D.E. Worth, E.C. Huffman, J.A. Brierley, B.G. McConkey, J. Yang, J.J. Hutchinson, R.L. Desjardins, R. Lemke, S. Gameda. 2008b. Estimation of N<sub>2</sub>O emissions from agricultural soils in Canada. II. 1990–2005 Inventory. *Can. J. Soil Sci.* 88: 655–69.
- Rothrock, C. S. 1992. Tillage Systems and Plant Disease. *Soil Sci.* 154: 308–15.
- Roy, A.K., C. Wagner-Riddle, B. Deen, J. Lauzon, and T. Bruulsema. 2014. Nitrogen application rate, timing and history effects on nitrous oxide emissions from corn (*Zea Mays* L.). *Can. J. Soil Sci.* 94: 563–73.
- Röver, M., O. Heinemeyer, and E.A. Kaiser. 1998. Microbial induced nitrous oxide emissions from an arable soil during winter. *Soil Biol. Biochem.* 30: 1859–65.
- Rudaz, A.O., E.A. Davidson, and M.K. Firestone. 1991. Sources of nitrous oxide production following wetting of dry soil. *FEMS Microbiol. Ecol.* 85: 117–24. doi:10.1139/CJSS2013-118.
- Sainju, U.M., J.D. Jabro, and W.B. Stevens. 2008. Soil carbon dioxide emission and carbon sequestration as influenced by irrigation, tillage, cropping system, and nitrogen fertilization. *J. Environ. Qual.* 37: 98–106.
- Sainju, U.M., W.B. Stevens, T. Caesar-TonThat, and M.A. Liebig. 2012. Soil greenhouse gas emissions affected by irrigation, tillage, crop rotation, and nitrogen fertilization. *J. Environ. Qual.* 41: 1774-86.
- Saskatchewan Agriculture, Food and Rural Revitalization (SAFRR). 2003. Irrigation in Saskatchewan. Outlook. SK. Available at [http://www.agriculture.gov.sk.ca/adx/asp/adxGetMedia.aspx?DocID=2088,2015,2000,1974,1973,204,Documents&MediaID=1379&Filename=0708budge\\_tbrochure.pdf](http://www.agriculture.gov.sk.ca/adx/asp/adxGetMedia.aspx?DocID=2088,2015,2000,1974,1973,204,Documents&MediaID=1379&Filename=0708budge_tbrochure.pdf) (verified 15 August 2017)
- Saskatchewan Irrigation Projects Association (SIPA). 2008a. A time to irrigate. Volume 1. Outlook, Saskatchewan, Canada. Available at <http://www.irrigationsaskatchewan.com/SIPA/publications/publications-major-studies/> (verified 7 August 2017).
- Saskatchewan Irrigation Projects Association (SIPA). 2008b. A time to irrigate. Volume 2. Outlook, Saskatchewan, Canada. Available at <http://www.irrigationsaskatchewan.com/SIPA/publications/publications-major-studies/> (verified 7 August 2017).



- Schlegel, A.J., C.A. Grant, and J.L. Havlin. 2005. Challenging approaches to nitrogen fertilizer recommendations in continuous cropping systems in the Great Plains. *Agron. J.* 97: 391–98.
- Smith, E.G., B.M. Upadhyay, M.L. Favret, and R.E. Karamanos. 2010. Fertilizer response for hybrid and open-pollinated canola and economic optimal nutrient levels. *Can. J. Plant Sci.* 90: 305–10.
- Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N.H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello. 2014. Agriculture, forestry and other land use (AFOLU). In: *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Snyder, C.S., T.W. Bruulsema, T.L. Jensen, and P.E. Fixen. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* 133: 247–266.
- Snyder, C., E. Davidson, P. Smith, and R. Venterea. 2014. Agriculture: sustainable crop and animal production to help mitigate nitrous oxide emissions. *Curr. Opin. Environ. Sustain.* 9–10: 46–54.
- Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood and D. Wratt, 2007. Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Statistics Canada. 2016. Environment factsheets: Irrigation methods and conservation practices on Canadian farms, 2014. Available at <http://www.statcan.gc.ca/pub/16-508-x/16-508-x2016001-eng.htm> (verified 24 May 2018).

- Statistics Canada. 2017a. Saskatchewan remains the breadbasket of Canada. Catalogue no. 95-640-X. Available at <https://www.statcan.gc.ca/pub/95-640-x/2016001/article/14807-eng.htm> (verified 17 May 2018).
- Statistics Canada. 2017b. Table 001-0068 - Fertilizer shipments to Canadian agriculture and export markets, by product type and fertilizer year, cumulative data, annual (metric tonnes), CANSIM (database) (verified 18 September 2017).
- Thomas, R.L., R.W. Sheard, and J.R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. *Agron. J.* 59: 240-243.
- Tollefson, L.C. and T.J. Hogg. 1997. Irrigation sustainability - Saskatchewan activity. *Can. Water Resour. J.* 22: 457-465. doi:10.4296/cwrj2204457.
- Tomasiewicz, D. 2017. Irrigation and Fertilization Practices for Irrigated Production Systems in Saskatchewan. Annual Report, ADF #20130229.
- Topham, H.L. 1982. History of irrigation in Western Canada, Prairie Farm Rehabilitation Administration, Regina.
- van Kessel, C. R. Venterea, J. Six, M.A. Adviento-Borbe, B. Linnquist, K.J. van Groenigen. 2013. Climate, duration, and N placement determine N<sub>2</sub>O emissions in reduced tillage systems: A meta-analysis. *Global Change Biol.* 19: 33-44.
- van Veen, J. A., E. Liljeroth, L.J.A. Lekkerkerk, and S.C. van de Geijn. 1991. Carbon fluxes in plant-soil systems at elevated atmospheric CO<sub>2</sub> levels. *Ecological Applications* 1: 175-81.
- Venterea, R.T. and J.A. Coulter. 2015. Split application of urea does not decrease and may increase nitrous oxide emissions in rainfed corn. *Agron. J.* 107: 337-348.
- Venterea, R.T., J.A. Coulter, and M.S. Dolan. 2016. Evaluation of intensive “4R” strategies for decreasing nitrous oxide emissions and nitrogen surplus in rainfed corn. *J. Environ. Qual.* 45: 1186-1195.
- Venterea, R.T., A.D. Halvorson, N. Kitchen, M.A. Liebig, M.A. Cavigelli, S.J.D. Grosso, P.P. Motavalli, K.A. Nelson, K.A. Spokas, B.P. Singh, C.E. Stewart, A. Ranaivoson, J. Strock, and H. Collins. 2012. Challenges and opportunities for mitigating nitrous oxide emissions from fertilized cropping systems. *Front. Ecol. Environ.* 10: 62-570.
- Wagner-Riddle, C. and G.W. Thurtell. 1998. Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. *Nutrient Cycling in Agroecosystems* 52: 151-63.

- Wright, G.C., C.J. Smith, and M.R. Woodroffe. 1988. The Effect of irrigation and nitrogen fertilizer on rapeseed (*Brassica Napus*) production in South-Eastern Australia. I. Growth and seed yield. *Irrigation Sci.* 9: 15–25.
- Xu, X., H. Tian, and D. Hui. 2008. Convergence in the relationship of CO<sub>2</sub> and N<sub>2</sub>O exchanges between soil and atmosphere within terrestrial ecosystems. *Global Change Biol.* 14: 1651–1660.
- Yadvinder-Singh, S., S. Malhi, M. Nyborg, and E.G. Beauchamp. 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.
- Yan X., Hosen, Y. and Yagi, K. 2001. Nitrous oxide and nitric oxide emissions from maize field plots as affected by N fertilizer type and application method. *Biol. Fertil. Soils* 34: 297–303.
- Zebarth, B.J., P. Rochette, D.L. Burton, and M. Price. 2008. Effect of fertilizer nitrogen management on N<sub>2</sub>O emissions in commercial corn fields. *Can. J. Soil Sci.* 88: 189–195. doi:10.4141/CJSS06010.
- Zebarth, B.J., E. Snowdon, D.L. Burton, C. Goyer, and R. Dowbenko. 2012. Controlled release fertilizer product effects on potato crop response and nitrous oxide emissions under rain-fed production on a medium-textured soil. *Can. J. Soil Sci.* 92: 759–769. doi:10.4141/cjss2012-008
- Zou, J., Y. Huang, L. Zong, X. Zheng, and Y. Wang. 2004. Carbon dioxide, methane, and nitrous oxide emissions from a rice-wheat rotation as affected by crop residue incorporation and temperature. *Adv. Atmos. Sci.* 21: 691–698.

## **APPENDIX**

## A. PLOT MAPS OF THE STUDY AREA

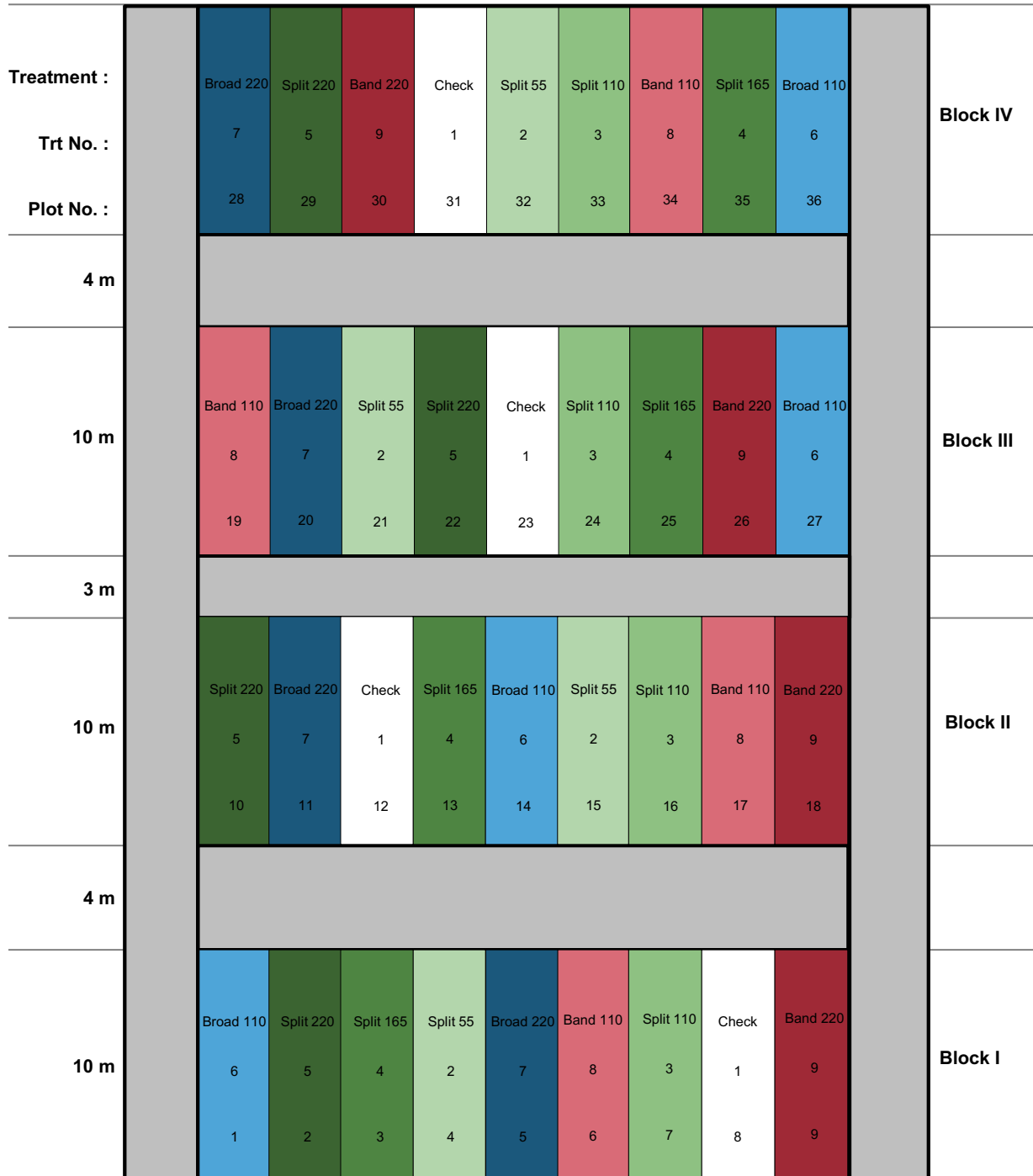


Figure A.1. Plot map for 2014 study area on Field #6. Individual plots were 3.048 m wide.

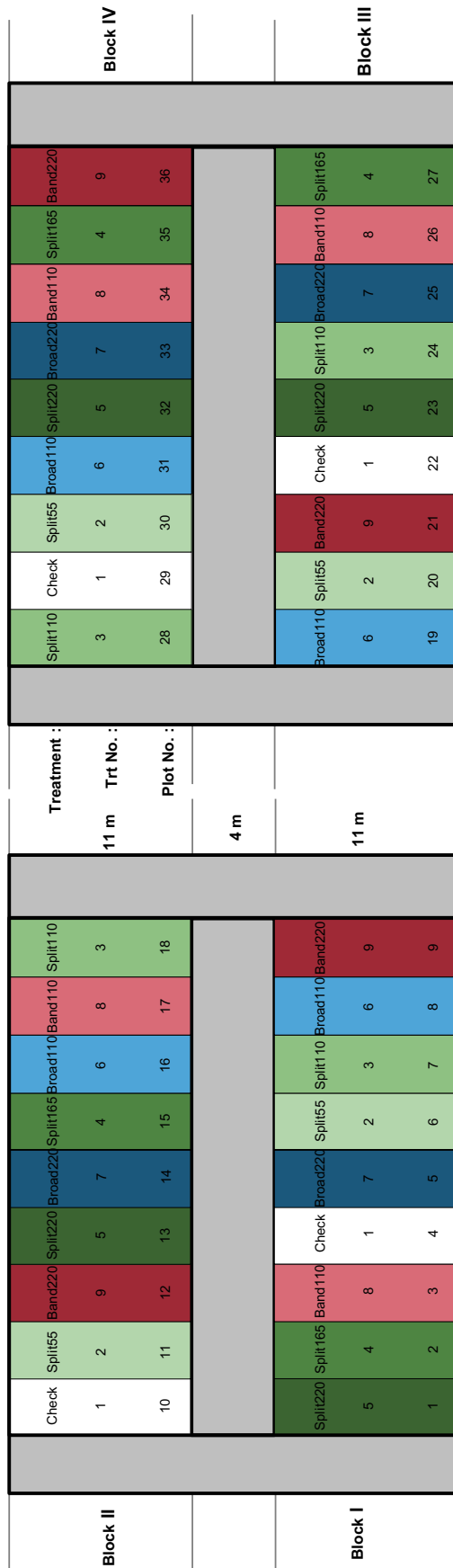


Figure A.2. Plot map for 2015 study area on Field #12. Individual plots were 3.048 m wide.

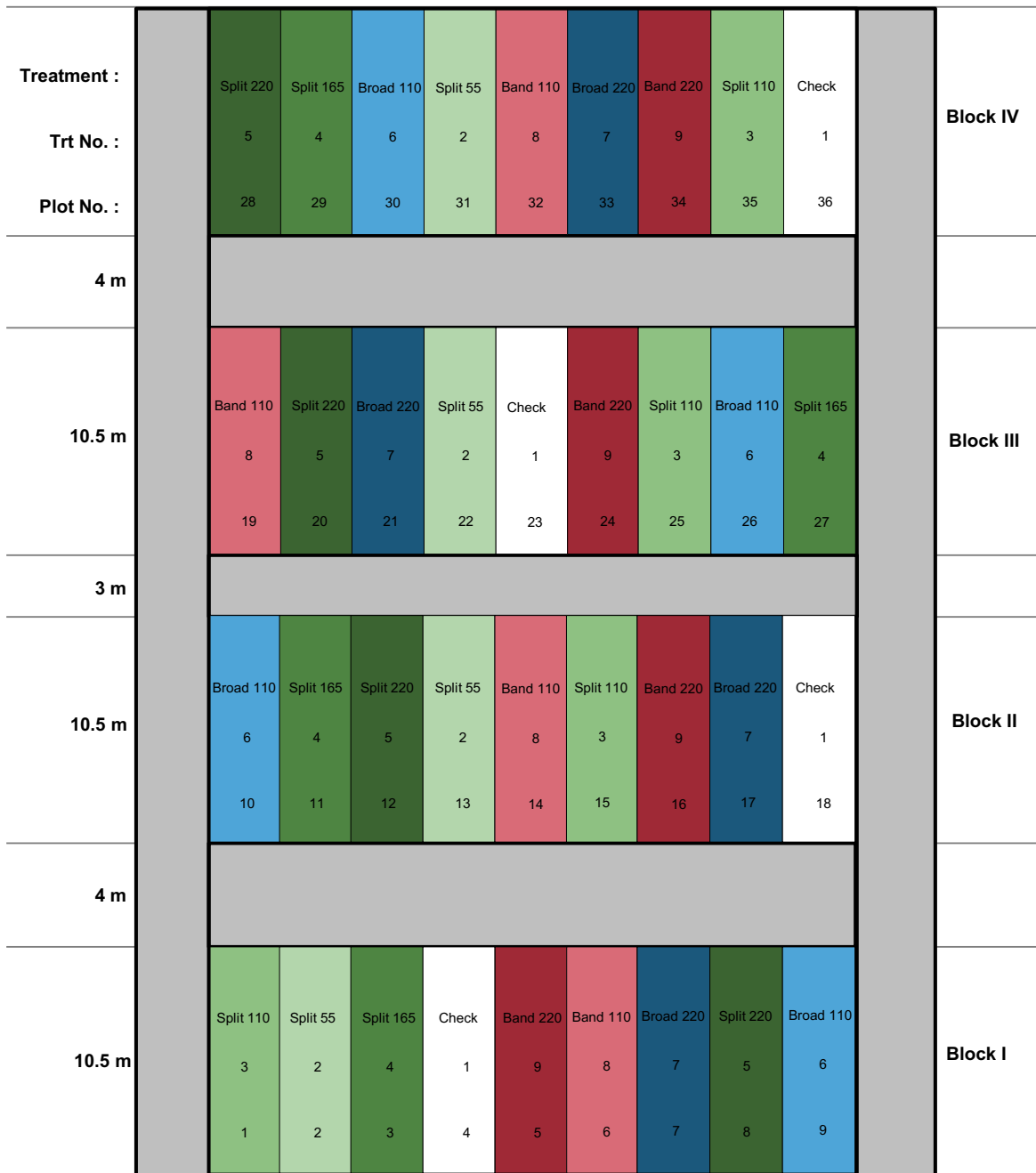
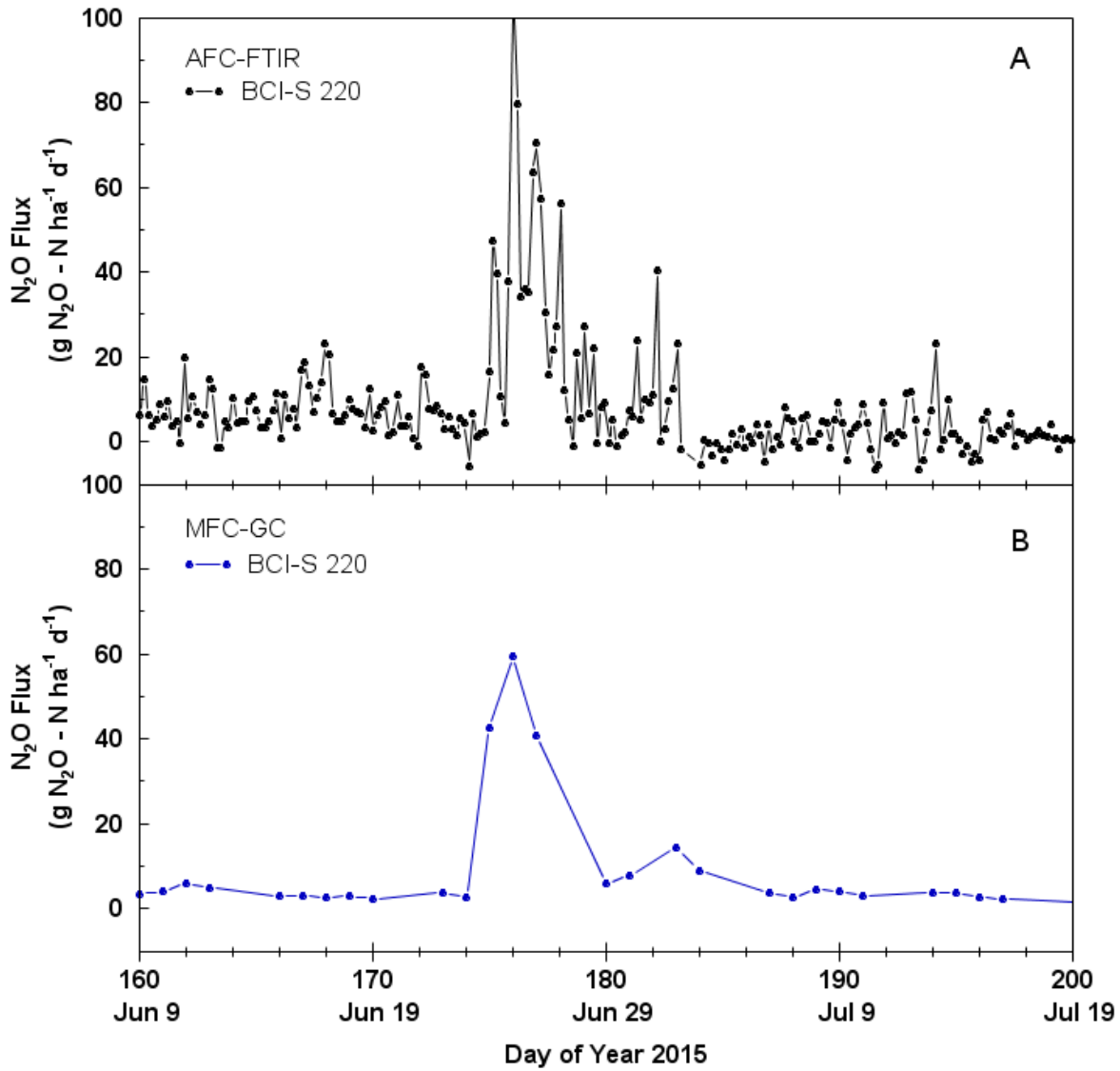


Figure A.3. Plot map for 2016 study area on Field #6. Individual plots were 3.048 m wide.

## B. AFC-FTIR DATA



**Figure B.1.** Comparison of N<sub>2</sub>O flux from (A) automated (AFC-FTIR) and (B) manual (MFC-GC) measurements from the BCI-S 220 treatment. This data shows that results from manual measurements appear as one large peak during an emission event where automated measurements have several peaks over the same period, and during low flux periods the AFC-FTIR picks up small fluctuations more than manual sampling.



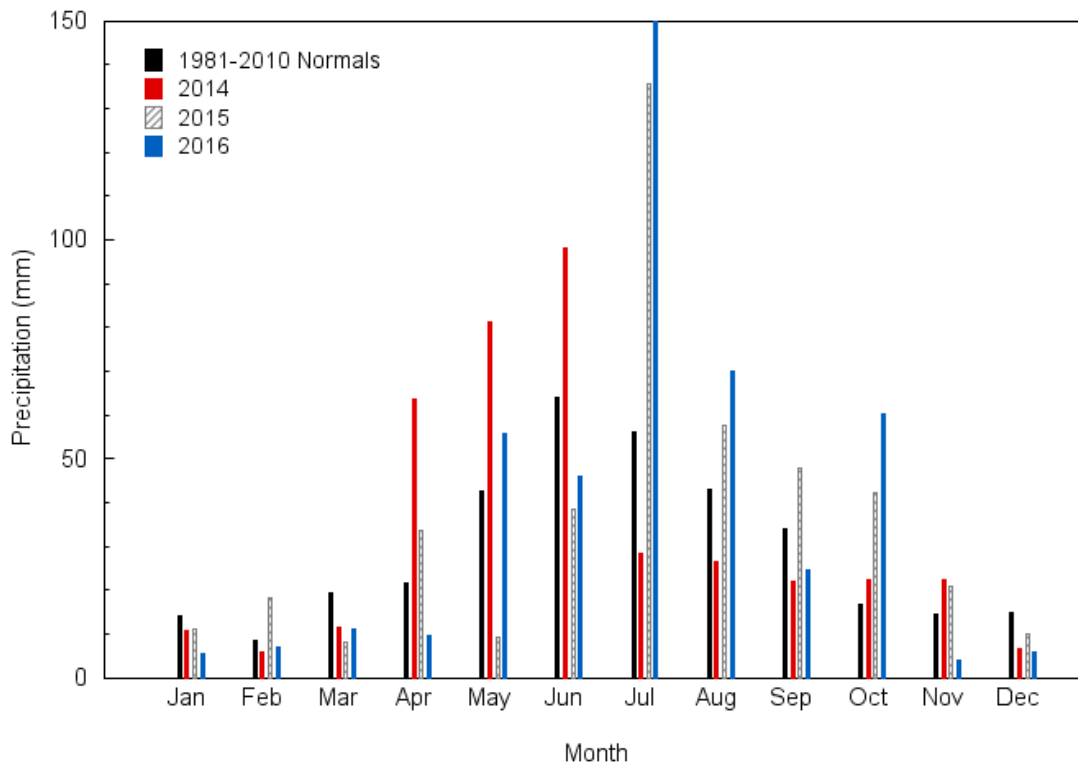
## C. CLIMATE DATA

**Table C.1.** Total monthly rainfall for the three years of study and the 20-year average monthly precipitation at the Outlook weather station. Data was taken from the weather station due to its proximity to study sites.

<b>Month</b>	<b>1981-2010</b>	<b>2014</b>	<b>2015</b>	<b>2016</b>	<b>2017</b>
	<i>mm</i>				
January	13.9	10.7	10.9	5.50	7.10
February	8.60	5.90	18.3	6.90	8.00
March	19.3	11.5	8.0	11.0	13.6
April	21.6	63.7	33.6	9.50	16.9
May	42.6	81.2	9.3	55.7	32.9
June	63.9	98.2	38.6	45.8	
July	56.1	28.4	135.4	195	
August	42.8	26.5	57.5	69.9	
September	34.1	21.9	47.9	24.4	
October	16.6	22.5	42.2	60.2	
November	14.6	22.3	20.7	3.80	
December	14.7	6.50	10.1	6.00	
<b>Growing season</b>	<b>240</b>	<b>256</b>	<b>289</b>	<b>390</b>	---
<b>Total</b>	<b>349</b>	<b>399</b>	<b>433</b>	<b>493</b>	---

**Table C.2.** The 20-year mean monthly air temperatures ( $\pm$  SD) and mean monthly air temperature during the study measured at the Outlook weather station.

<b>Month</b>	<b>1981-2010</b>	<b>2014</b>	<b>2015</b>	<b>2016</b>	<b>2017</b>
	$^{\circ}\text{C}$				
January	-13 $\pm$ 4.8	-13	-9.6	-12	-11
February	-10 $\pm$ 4.3	-18	-15	-5.2	-7.5
March	-3.4 $\pm$ 3.3	-9.3	-0.9	0.2	-3.6
April	5.3 $\pm$ 1.9	2.3	6.0	6.0	4.5
May	12 $\pm$ 1.6	11	10	14	12
June	16 $\pm$ 1.5	15	17	17	16
July	19 $\pm$ 1.4	18	19	19	20
August	18 $\pm$ 1.4	18	17	17	18
September	12 $\pm$ 2.0	13	13	12	13
October	5.1 $\pm$ 1.7	7.8	7.7	3.5	5.4
November	-4.1 $\pm$ 3.6	-8.0	-1.6	2.3	-7.1
December	-11 $\pm$ 4.7	-7.8	-7.7	-12	-9.9



**Figure C.1.** Total monthly precipitation of the three years of study and the 20-year average monthly precipitation at the Outlook weather station. Data was taken from the weather station due to its proximity to study sites.

## D. CONTRASTS

Treatment		Check	BCI-S 55	BCI-S 100	BCI-S 165	BCI-S 220	BCI- O 110	BCI- O 220	SB 110	SB 220
<b>Treatment</b>	GC	1	2	3	4	5	6	7	8	9
<b>Number</b>	AFC	10	11	12	13	14	-	-	15	16

To compare the cumulative N<sub>2</sub>O emissions from the AFC-FTIR and MFC-GC systems, each treatment that contained automated chambers was compared to the corresponding manual sampling plots.

Contrast AFC-GC            C 1 2 3 4 5 8 9 C 10 11 12 13 14 15 16

For the rate treatments, the check and four BCI-S N rates (0, 55, 110, 165, 220 kg N ha<sup>-1</sup>) were contrasted.

Contrast Rate            C 1 C 2 C 3 C 4 C 5

For the timing treatments, the BCI-O and BCI-S treatments were contrasted at both rates (110 and 220 kg N ha<sup>-1</sup>) to determine the overall effect of timing regardless of N rate.

Contrast Timing            C 3 5 C 6 7

For the placement treatments, the BCI-O and SB treatments were contrasted at both rates (110 and 220 kg N ha<sup>-1</sup>) to determine the overall effect of placement regardless of N rate.

Contrast Placement        C 6 7 C 8 9

## E. SOIL CHARACTERISTICS

**Table E.1.** Extractable soil nitrate ( $\text{NO}_3^-$ ) and ammonium ( $\text{NH}_4^+$ ) from the Field 6 site in spring 2015<sup>†</sup>. Values presented are means (n = 3). Nitrate and ammonia extracts were prepared using 2 M KCl.

Plot	Treatment	Rate <i>kg ha<sup>-1</sup></i>	Nitrate $\text{NO}_3\text{-N}$			Ammonium $\text{NH}_4\text{-N}$		
			<i><math>\mu\text{g N g soil}^{-1}</math></i>			<i><math>\mu\text{g N g soil}^{-1}</math></i>		
			0-15 cm	15-30 cm	30-60 cm	0-15 cm	15-30 cm	30-60 cm
1	BCI-O	110	8.42	15.8	39.8	0.56	0.93	0.58
2	BCI-S	220	16.2	22.7	45.9	0.70	0.59	0.56
3	BCI-S	165	36.6	61.7	63.0	0.99	1.14	0.72
4	BCI-S	55	11.3	14.5	31.1	0.62	0.86	0.61
5	BCI-O	220	28.2	27.5	39.3	1.03	0.67	0.68
6	SB	110	42.7	54.9	41.7	0.62	1.42	0.97
7	BCI-S	110	69.0	58.1	47.4	0.61	0.85	0.56
8	Check	0	92.8	63.9	59.6	1.03	0.86	1.05
9	SB	220	60.0	56.6	51.6	0.88	2.60	0.94
10	BCI-S	220	42.6	38.6	46.1	1.07	0.96	1.23
11	BCI-O	220	21.9	33.0	42.2	1.22	1.16	1.19
12	Check	0	26.8	35.1	41.3	0.71	0.74	0.75
13	BCI-S	165	16.6	33.9	42.1	0.70	0.94	0.68
14	BCI-O	110	22.8	27.7	39.9	0.67	0.80	0.64
15	BCI-S	55	21.1	32.0	42.7	0.72	0.76	0.36
16	BCI-S	110	25.5	32.7	36.9	0.46	0.48	0.86
17	SB	110	53.7	51.1	50.2	1.02	1.38	1.36
18	SB	220	38.8	33.3	37.3	0.59	0.39	0.58
19	SB	110	27.0	19.3	36.2	0.78	0.38	0.56
20	BCI-O	220	16.4	9.43	18.3	0.49	0.62	0.40
21	BCI-S	55	19.8	16.8	24.8	0.97	0.88	1.30
22	BCI-S	220	9.82	13.2	24.6	0.61	0.68	0.55
23	Check	0	16.4	22.7	40.0	0.66	0.99	0.75
24	BCI-S	110	18.6	35.0	36.8	0.78	0.90	0.69
25	BCI-S	165	27.4	35.1	36.7	1.46	1.03	0.88
26	SB	220	31.9	42.9	44.4	0.75	0.77	0.67
27	BCI-O	110	21.5	33.8	37.7	0.96	1.06	0.94
28	BCI-O	220	43.5	36.5	50.6	1.13	1.01	1.02
29	BCI-S	220	58.2	57.5	64.8	1.20	1.34	1.67
30	SB	220	28.2	33.1	52.1	0.76	1.82	4.87
31	Check	0	15.9	24.6	34.1	0.71	1.09	4.38
32	BCI-S	55	19.8	32.6	48.9	0.72	1.09	1.37
33	BCI-S	110	30.0	24.2	34.1	0.96	0.76	1.19
34	SB	110	25.1	26.7	40.8	0.69	1.06	0.82
35	BCI-S	165	45.3	52.6	54.0	0.53	0.42	0.49
36	BCI-O	110	16.3	26.9	31.3	0.73	0.63	0.74

<sup>†</sup>**Note:** soil samples collected after harvest in fall 2014 became contaminated during processing; consequently, the plots were resampled in spring 2015.

**Table E.2.** Extractable nitrate ( $\text{NO}_3^-$ ), ammonium ( $\text{NH}_4^+$ ) from the Field 12 site in fall 2015. Soil samples were collected after harvest. Nitrate and ammonia extracts were prepared using 2 M KCl.

Plot	Treatment	Rate <i>kg ha<sup>-1</sup></i>	Nitrate $\text{NO}_3\text{-N}$ <i><math>\mu\text{g N g soil}^{-1}</math></i>				Ammonium $\text{NH}_4\text{-N}$ <i><math>\mu\text{g N g soil}^{-1}</math></i>			
			0-30 cm	30-60 cm	60-90 cm	90-120 cm	0-30 cm	30-60 cm	60-90 cm	90-120 cm
1	BCI-S	220	4.83	2.45	1.67	3.64	5.56	6.30	4.62	5.05
2	BCI-S	165	3.96	1.78	0.57	1.92	5.28	5.84	4.30	5.00
3	SB	110	3.15	1.28	0.46	2.24	3.16	4.93	4.53	5.14
4	Check	0	2.58	1.16	-0.01	1.54	3.77	5.65	4.76	6.48
5	BCI-O	220	5.74	5.43	0.57	3.03	3.84	4.11	4.85	4.66
6	BCI-S	55	3.24	1.82	-0.16	2.03	3.22	3.64	3.83	4.08
7	BCI-S	110	4.09	1.92	0.64	2.88	3.94	4.34	3.96	3.67
8	BCI-O	110	2.75	1.62	0.06	1.75	4.02	4.17	3.14	3.91
9	SB	220	6.92	5.01	0.74	1.62	3.44	3.93	3.57	3.55
10	Check	0	3.60	2.36	-0.14	1.90	2.99	4.10	2.47	3.00
11	BCI-S	55	4.43	2.08	0.95	5.28	2.81	3.85	3.34	4.30
12	SB	220	8.52	15.57	2.14	6.15	3.71	3.32	2.97	3.65
13	BCI-S	220	8.56	10.70	1.64	5.09	4.13	3.65	3.72	5.22
14	BCI-O	220	7.85	9.31	1.90	4.53	3.70	3.95	2.94	4.03
15	BCI-S	165	7.80	5.59	1.43	4.28	4.39	4.31	3.60	3.33
16	BCI-O	110	4.36	2.82	0.81	4.65	4.62	4.63	3.51	8.62
17	SB	110	7.37	4.65	5.83	8.01	7.09	3.74	3.75	3.21
18	BCI-S	110	4.99	3.01	4.45	9.96	5.09	3.50	3.76	4.94
19	BCI-O	110	4.14	2.15	1.48	2.93	3.81	4.09	5.27	6.98
20	BCI-S	55	2.24	1.83	0.36	1.68	4.06	3.12	2.94	3.78
21	SB	220	6.66	3.55	1.63	2.55	3.25	2.76	3.58	4.46
22	Check	0	3.24	2.00	0.42	1.25	3.12	3.88	4.86	4.92
23	BCI-S	220	6.81	7.74	1.90	3.14	3.74	2.68	3.79	5.65
24	BCI-S	110	4.09	2.50	1.11	4.53	3.77	2.74	2.34	1.76
25	BCI-O	220	7.68	6.42	2.14	3.07	3.94	2.96	3.32	3.17
26	SB	110	3.18	2.54	0.71	2.47	2.92	3.07	2.92	4.17
27	BCI-S	165	5.77	5.33	0.87	2.97	3.55	2.95	3.02	5.10
28	BCI-S	110	5.16	5.96	2.96	5.88	3.40	2.06	3.56	7.81
29	Check	0	3.25	2.31	0.55	2.72	3.58	2.57	3.42	2.96
30	BCI-S	55	4.11	3.45	1.40	2.70	3.36	2.76	3.10	2.04
31	BCI-O	110	4.92	3.65	2.72	5.79	3.84	2.72	3.30	3.80
32	BCI-S	220	6.58	7.68	2.66	5.57	3.93	2.29	3.27	3.40
33	BCI-O	220	13.33	7.19	4.30	7.14	4.42	2.89	3.56	3.49
34	SB	110	6.17	3.57	1.60	4.93	4.65	3.42	4.04	4.15
35	BCI-S	165	5.35	3.37	2.56	4.86	4.13	2.66	3.81	3.22
36	SB	220	8.84	7.85	3.96	5.45	4.94	3.11	3.62	5.18

**Table E.3.** Soil sampling results for extractable nitrate (NO<sub>3</sub><sup>-</sup>), ammonium (NH<sub>4</sub><sup>+</sup>) from the Field 6 site in fall 2016. Soil samples were collected after harvest. Nitrate and ammonia extracts were prepared using 2 M KCl.

Plot	Treatment	Rate <i>kg ha<sup>-1</sup></i>	Nitrate NO <sub>3</sub> -N <i>µg N g soil<sup>-1</sup></i>				Ammonium NH <sub>4</sub> -N <i>µg N g soil<sup>-1</sup></i>			
			0-30 cm	30-60 cm	60-90 cm	90-120 cm	0-30 cm	30-60 cm	60-90 cm	90-120 cm
1	BCI-S	110	9.39	3.32	8.43	19.1	3.44	3.63	3.16	2.44
2	BCI-S	55	11.2	4.97	11.5	29.2	3.00	3.45	2.56	2.40
3	BCI-S	165	14.6	7.52	18.0	42.1	3.45	3.22	2.52	2.52
4	Check	0	8.37	4.54	7.46	34.5	3.51	3.48	2.73	2.58
5	SB	220	19.0	19.6	15.9	29.5	3.58	3.76	2.52	2.02
6	SB	110	6.56	3.36	12.4	33.1	3.57	3.67	3.03	2.28
7	BCI-O	220	15.4	6.38	20.4	42.6	3.68	3.79	2.74	2.56
8	BCI-S	220	25.7	25.0	17.8	37.3	3.89	4.04	3.32	2.17
9	BCI-O	110	8.61	5.41	13.5	29.0	3.25	3.20	2.48	1.90
10	BCI-O	110	11.2	7.96	14.7	38.9	3.22	3.25	2.61	2.64
11	BCI-S	165	15.7	6.29	21.7	33.7	3.05	3.23	2.69	2.80
12	BCI-S	220	26.6	16.4	27.8	35.5	3.17	3.35	2.63	2.21
13	BCI-S	55	8.16	3.99	8.30	32.5	3.07	3.26	2.67	2.49
14	SB	110	8.54	4.61	8.25	31.4	3.41	3.62	3.60	2.67
15	BCI-S	110	9.72	6.13	21.2	5.50	3.18	2.89	3.01	3.11
16	SB	220	15.7	20.2	11.0	7.01	3.64	3.46	3.39	2.54
17	BCI-O	220	8.88	7.23	6.45	19.8	3.02	3.66	3.50	2.82
18	Check	0	5.47	3.09	3.18	19.7	3.41	3.31	3.28	2.94
19	SB	110	13.4	14.5	9.32	18.7	3.64	3.70	2.79	3.19
20	BCI-S	220	17.9	8.77	9.54	18.1	3.38	3.87	2.55	2.30
21	BCI-O	220	11.4	24.8	11.8	22.8	2.57	3.81	2.52	2.35
22	BCI-S	55	6.27	4.74	2.04	5.97	3.31	3.80	3.17	2.67
23	Check	0	8.21	5.45	2.94	11.3	3.77	4.05	3.68	2.98
24	SB	220	16.3	24.1	13.4	25.5	3.83	3.96	3.41	2.60
25	BCI-S	110	9.88	4.79	6.61	20.6	3.59	4.18	3.54	2.96
26	BCI-O	110	11.2	5.63	3.89	20.0	3.24	3.93	3.25	2.91
27	BCI-S	165	16.5	10.9	4.58	15.9	3.75	3.15	3.14	2.72
28	BCI-S	220	14.5	14.5	17.9	21.1	3.36	3.98	3.39	3.20
29	BCI-S	165	15.7	11.6	10.2	12.9	3.26	3.45	3.47	2.82
30	BCI-O	110	10.2	6.16	9.48	26.1	3.27	3.60	2.96	3.46
31	BCI-S	55	9.37	3.22	3.45	17.3	3.27	3.08	2.43	2.24
32	SB	110	10.7	4.91	10.9	15.6	2.77	2.87	2.69	1.96
33	BCI-O	220	9.81	13.3	8.47	18.8	3.07	3.57	3.04	2.97
34	SB	220	12.1	24.3	14.4	6.82	2.91	2.95	2.63	2.62
35	BCI-S	110	6.02	4.03	12.3	34.7	2.60	2.91	2.49	1.83
36	Check	0	5.86	3.73	10.8	30.4	2.82	2.98	2.60	1.86

## F. CO<sub>2</sub> DATA

**Table F.1.** Pearson product moment correlation for the daily N<sub>2</sub>O and CO<sub>2</sub> emissions from the growing season.

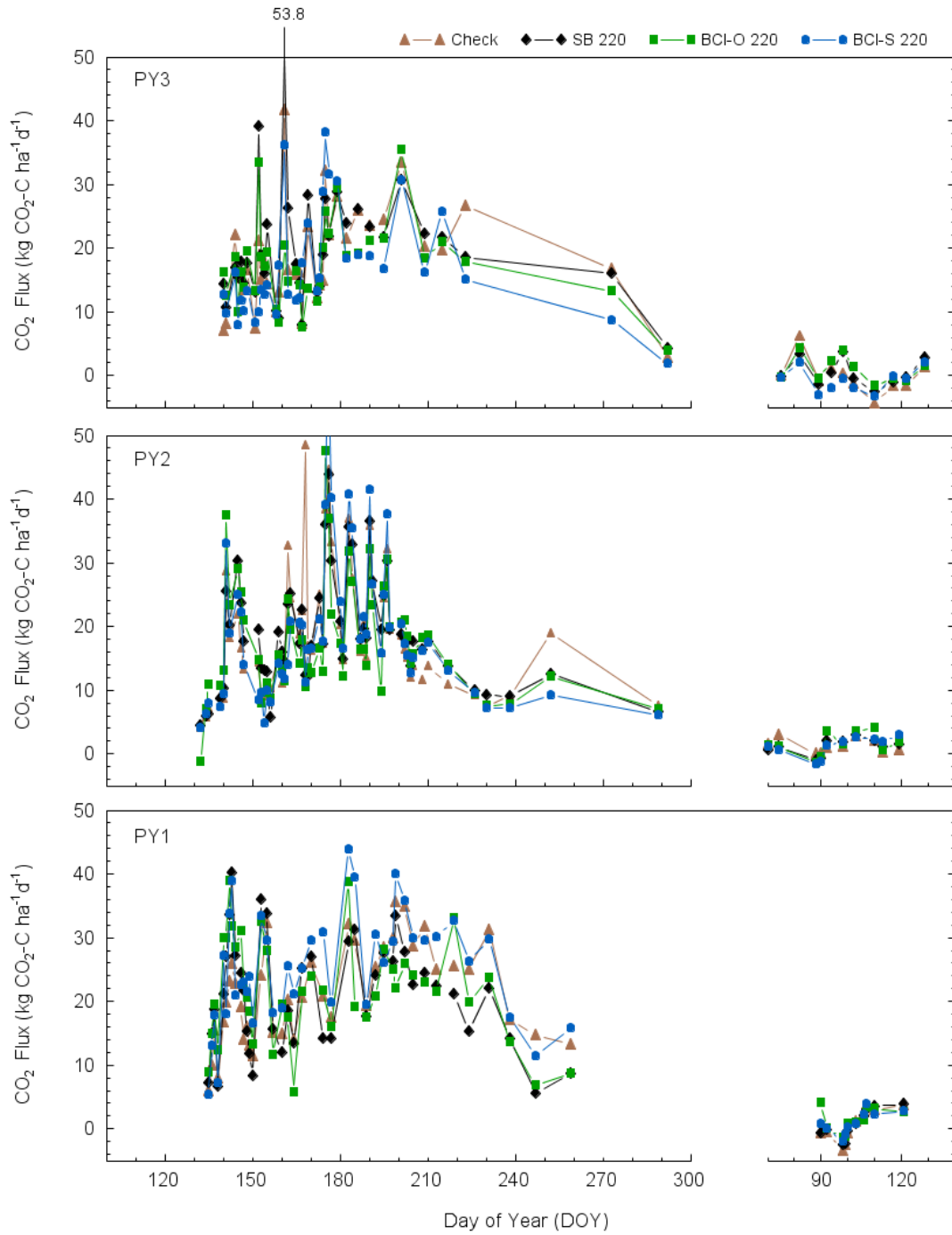
Treatment	Rate	2014	2015	2016
		(n = 164)	(n = 224)	(n = 144)
		Correlation (r)		
Check	0	0.247 **	0.050 ns	0.476 ***
Split	55	0.249 **	0.434 ***	0.453 ***
	110	0.439 ***	0.591 ***	0.408 ***
	165	0.433 ***	0.594 ***	0.366 ***
	220	0.352 ***	0.700 ***	0.541 ***
Broadcast and Incorporated	110	0.508 ***	0.206 **	0.119 ns
	220	0.376 ***	0.201 **	0.317 ***
Side-banded	110	0.255 ***	0.137 *	0.479 ***
	220	0.420 ***	0.029 ns	0.638 ***

\* P ≤ 0.05

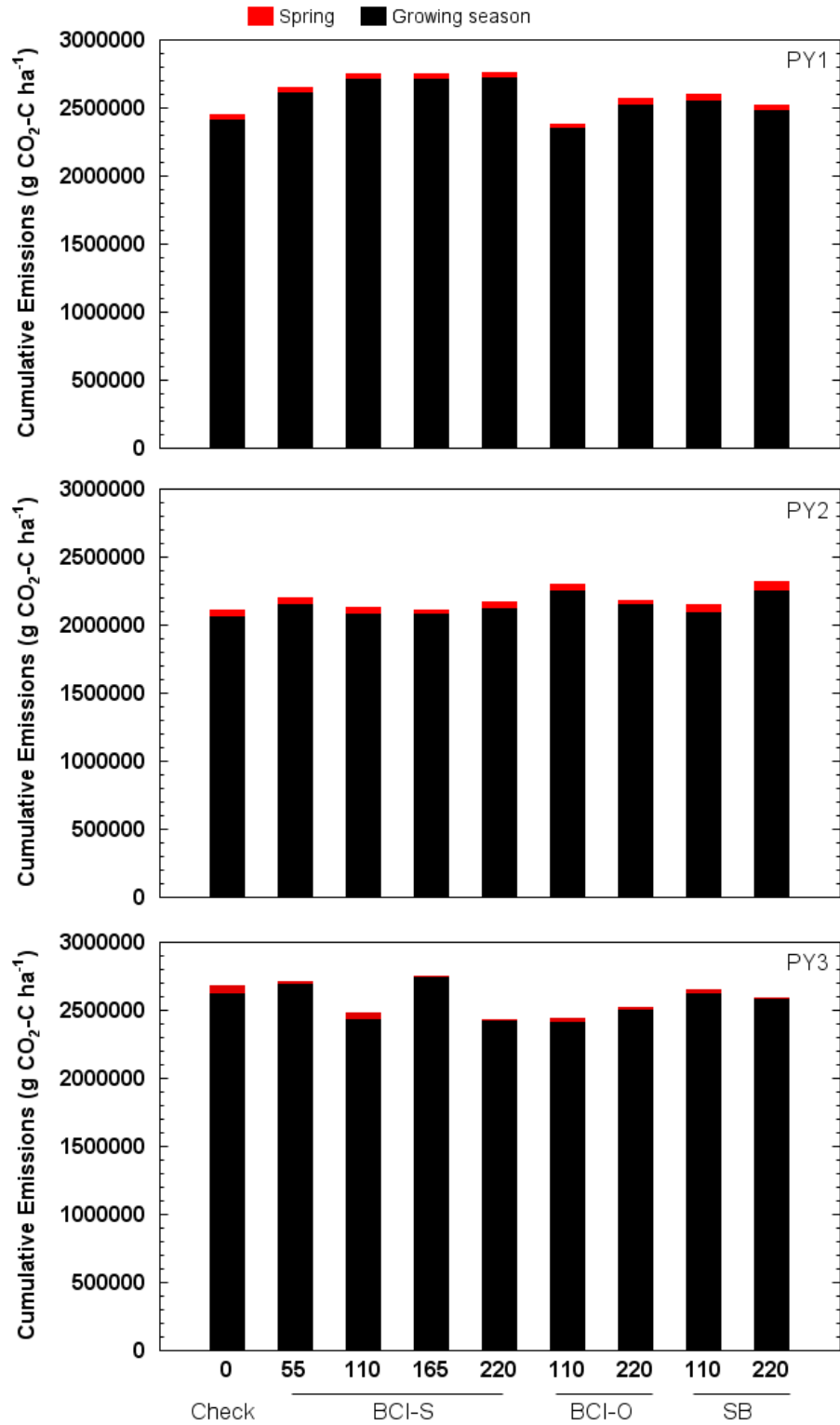
\*\* P ≤ 0.01

\*\*\* P ≤ 0.001





**Figure F.1.** The average daily CO<sub>2</sub> flux that shows the effect of the rate of urea fertilizer on check plots and all treatments at 220 kg N ha<sup>-1</sup> in PY1 (2014/15), PY2 (2015/16) and PY3 (2016/17). Gas samples were collected using the manual flux chamber (MFC) system and analyzed using gas chromatography (GC).



**Figure F.2.** Cumulative CO<sub>2</sub> emissions from PY1 (2014/15), PY2 (2015/16), and PY3(2016/17). The black bars represent the growing season and the red bars represent the spring emissions. There was no significant difference in cumulative emissions between treatments ( $P = 0.05$ ).

## G. PYTHON SCRIPTS

All Python scripts were developed by Frank Krijnen and are included here with his permission.

**Script G.1. Merge Results.** This script takes the data from each day that is saved as a separate folder, and merges them into an excel file that gets used in script G.2.

```
from Tkinter import *
import tkFileDialog
import tkMessageBox
import os
import string
import datetime
import time
import csv
import numpy

def askopenresultsfilename():
    # get filename
    fileopen_opt = options = {}
    options['initialdir'] = 'C:\FTIRtools'
    options['parent'] = root
    options['title'] = 'Choose a folder with results subfolders to open'
    global inputfoldername
    inputfoldername = tkFileDialog.askdirectory(**fileopen_opt)

    # open file
    if inputfoldername:
        print "ok it seems to be working"
        os.chdir(inputfoldername)
        resultsfilename=datetime.datetime.now().strftime('%Y%m%d_%H%M%S') +
'_FTIR.csv'
        openresultsfile=open(resultsfilename, 'wb')
        resultswriter = csv.writer(openresultsfile, dialect='excel')

        resultswriter.writerow(['Epoch', 'DateTime', 'JulDate', 'JulTime', 'Date', 'Time',
'Line', 'Water_vapor_H2O', 'Carbon_dioxide_CO2', 'Nitrous_oxide_N2O',
'Methane_CH4', 'Ammonia_NH3', 'Ambient_pressure',
'Interferometer_temperature', 'IFG_peak_height'])

        sensorresultsfileName=datetime.datetime.now().strftime('%Y%m%d_%H%M%S')
+ '_SENSORS.csv'
        opensensorresultsfile=open(sensorresultsfileName, 'wb')
        sensorresultswriter = csv.writer(opensensorresultsfile,
dialect='excel')

        sensorresultswriter.writerow(['jultime', 'activeport', 'sensorport', 'chambertem
p', 'soiltemp', 'soilmoist', 'soilmoist2'])

        startjultime=float(startjultimeentry.get())
        endjultime=float(endjultimeentry.get())
        for r,d,f in os.walk(inputfoldername):
            for dirs in d:
                print dirs
                if os.path.isfile(dirs +"/RESULTS.TXT"):
                    openinputfile=open(dirs +"/RESULTS.TXT", 'rb')
```

```

        fd = numpy.genfromtxt(openinputfile, delimiter='\t',
dtype=None, names=True)
        print len(fd['Time'])

        c1=0
        for row in fd['Nitrous_oxide_N2O']:
            try:
                datetimestr=str(fd['Date'][c1])+" "+str(fd['Time'][c1])
                tempstructtime=time.strptime(datetimestr, "%Y-%m-%d
%H:%M:%S")

                julday=time.strptime("%j", tempstructtime)
                avgtime=time.strptime("%H:%M", tempstructtime)

                year=int(time.strptime("%Y", tempstructtime))
                month=int(time.strptime("%m", tempstructtime))
                day=int(time.strptime("%d", tempstructtime))
                hour=float(time.strptime("%H", tempstructtime))
                minute=float(time.strptime("%M", tempstructtime))
                second=float(time.strptime("%S", tempstructtime))

                floattime=float(hour)/24+float(minute/(24*60)+float(second/(24*3600)))
                julyeartime=float(year*1000)+ float(julday)+floattime
                jultime=float(julday)+floattime

                DATE_TIME=(datetime.datetime(year,month,day,int(hour),int(minute),int(second)
) - datetime.datetime(1970,1,1)).total_seconds()
                dateandtime=time.strptime("%Y/%m/%d %H:%M:%S",
tempstructtime)

                if jultime> startjultime and jultime < endjultime:

                resultswriter.writerow([DATE_TIME,dateandtime,julyeartime,jultime,fd['Date'][
c1],fd['Time'][c1],fd['Line'][c1],fd['Water_vapor_H2O'][c1],fd['Carbon_dioxid
e_CO2'][c1],fd['Nitrous_oxide_N2O'][c1],fd['Methane_CH4'][c1],fd['Ammonia_NH3
'][c1],fd['Ambient_pressure'][c1],
fd['Interferometer_temperature'][c1],fd['IFG_peak_height'][c1]])
            except:
                print "couln't read one"
                c1=c1+1
            openinputfile.close()
        else:
            print "no RESULTS.TXT in " + dirs

        if os.path.isfile(dirs +"/sensordata.txt"):
            openinputfile=open(dirs +"/sensordata.txt", 'rb')
            cleansensordata=[]

            for line in openinputfile:
                try:
                    #print line
                    if (line.__len__() > 5) :
                        numbers,xmldata=line.split("<",1)
                        activeport,sensorport=numbers.split("_",1)
                        if sensorport.isdigit():
                            # print numbers
                            shit,xmldata=xmldata.split("<TIME>",1)
                            longdatetime,xmldata=xmldata.split("</TIME>",1)

```

```

        print longdatetime
        shit,xmldata=xmldata.split("<CHAMBERTEMP>",1)

chambertemp,xmldata=xmldata.split("</CHAMBERTEMP>",1)
    # print chambertemp
    shit,xmldata=xmldata.split("<V2>",1)
    soiltemp,xmldata=xmldata.split("</V2>",1)
    #print soiltemp
    shit,xmldata=xmldata.split("<V3>",1)
    soilmoistv,xmldata=xmldata.split("</V3>",1)
    # print soilmoistv
    shit,xmldata=xmldata.split("<V4>",1)
    soilmoistv2,xmldata=xmldata.split("</V4>",1)

    soilmoistv=-3.14e-
7*(float(soilmoistv)*1000)**2+1.16e-3*float(soilmoistv)*1000-6.12e-1
    soilmoistv2=-3.14e-
7*(float(soilmoistv2)*1000)**2+1.16e-3*float(soilmoistv2)*1000-6.12e-1

    datetimestr=str(longdatetime)
    tempstructtime=time.strptime(datetimestr,
"%Y%m%d%H%M%S")

    julday=time.strptime("%j", tempstructtime)
    avgtime=time.strptime("%H:%M", tempstructtime)
    hour=float(time.strptime("%H", tempstructtime))
    minute=float(time.strptime("%M", tempstructtime))
    floattime=float(hour)/24+float(minute)/(24*60)
    jultime=float(julday)+floattime

    #if soiltemp > -10 and soiltemp < 50 and
soilmoistv > 0.05 and soilmoistv < 0.5:
        if float(soiltemp) > -10 and float(soiltemp) < 50
and soilmoistv > 0.05 and soilmoistv < 0.5:
            if jultime> startjultime and jultime <
endjultime:

sensorresultswriter.writerow([jultime,activeport,sensorport,chambertemp,soilt
emp,soilmoistv,soilmoistv2])
        except:
            print "found bad dataline"
            openinputfile.close()

    else:
        print "no sensordata.txt in " + dirs

    openresultsfile.close()

#
#-----GUI-----
#
#
# create a root TkInter frame
root = Tk()
root.title('FTIR results merger 20140602')
```

```

# _____ LOGO&TITLE _____
_____

uofslogo = PhotoImage(file="uofs.gif")
logo=Label(root, anchor=E, image=uofslogo, bg='darkgreen')
bigtitle = Label(root, anchor=W, font=('times', 20, 'bold'),
fg='white',bg='darkgreen', text="FTIR results merger ")
logo.grid(row=0,column=3,columnspan=1,sticky=[N,S,E,W])
bigtitle.grid(row=0,column=0,columnspan=3,sticky=[N,S,E,W])

# _____ OPTIONS _____
_____

optionstitle = Label(root, anchor=W, font=('times', 12, 'bold'),
text="options:")
optionstitle.grid(row=1,column=0, columnspan=3, sticky=[N,S,E,W])

startjultimeentrytitle = Label(root, anchor=W, text="start julian day (20.1)
:")
startjultimeentrytitle.grid(row=3,column=0, columnspan=1, sticky=[E])
startjultimeentry= Entry(root,width=4)
startjultimeentry.insert(0,"0.0")
startjultimeentry.grid(row=3,column=1, columnspan=1, sticky=[W])

endjultimeentrytitle = Label(root, anchor=W, text="end julian day (25.1):")
endjultimeentrytitle.grid(row=4,column=0, columnspan=1, sticky=[E])
endjultimeentry= Entry(root,width=4)
endjultimeentry.insert(0,"366.0")
endjultimeentry.grid(row=4,column=1, columnspan=1, sticky=[W])

# _____ CALC INDIVIDUAL _____
FLUXES
_____
f0=Frame(root,height=1, width=450, bg="grey")
f0.grid(row=24,column=0, columnspan=4, pady=5,sticky=S)

calcfluxtitle = Label(root, anchor=W, font=('times', 12, 'bold'), text="Merge
Calcmet results")
calcfluxtitle.grid(row=25,column=0, columnspan=4, sticky=[N,S,E,W])
calcfluxhelp = Label(root, anchor=W, text="Open a Calcmet results folder")
calcfluxhelp.grid(row=26,column=0, columnspan=4, sticky=[N,S,E,W])

buttonopenconcfile=Button(root, text='open calcmet results folder',
command=askopenresultsfilename)
buttonopenconcfile.grid(row=28,column=1,columnspan=1,sticky=[W])

#
#
_____

root.mainloop( )

```



```

def askopenresultsfilename():
    # get filename
    fileopen_opt = options = {}
    options['defaulttextension'] = '.csv'
    options['filetypes'] = [('csv files', '.csv'),('all files', '*.')]
    options['initialdir'] = 'C:\FTIRtools'
    options['initialfile'] = 'FTIR_CONCENTRATIONS.csv'
    options['parent'] = root
    options['title'] = 'Choose a csv file with merged results to open'
    global inputfilename
    inputfilename = tkFileDialog.askopenfilename(**fileopen_opt)

    # open file
    if inputfilename:
        openinputfile=open(inputfilename, 'rb')
        tempFileName, tempFileExtension = os.path.splitext(inputfilename)
        resultsfileName=tempFileName + '_FLUXES.csv'
        openresultsfile=open(resultsfileName, 'wb')
        if dosavetopdf.get()>0:
            pdffile = PdfPages(tempFileName + '_fluxes.pdf')

            ftirdata = numpy.genfromtxt(openinputfile, delimiter=',', dtype=None,
names=True)
            ftirdata=numpy.sort(ftirdata, order='Epoch')
            print len(ftirdata['Time'])
            amountrows=len(ftirdata['Time'])

            resultswriter = csv.writer(openresultsfile, dialect='excel')
            if doUnits.get()>0:

resultswriter.writerow(['port','epoch','julianday','avgtime','totaltime',
'jultime', 'n', 'co2interc (ul/l)', 'co2slope (ug C/(m2*s))',
'co2linr2','co2linp','co2stderr','co2slopeconf', 'n2ointerc (ul/l)',
'n2oslope (ug N/(m2*s))', 'n2olinr2','n2olinp', 'n2ostderr',
'n2oslopeconf','ch4interc (ul/l)', 'ch4slope (ug C/(m2*s))',
'ch4linr2','ch4linp', 'ch4stderr', 'ch4slopeconf','nh3interc', 'nh3slope',
'nh3linr2','nh3linp','nh3stderr','nh3slopeconf','interftemp','airpressure','h
2o','IFGheight'])
            else:

resultswriter.writerow(['port','epoch','julianday','avgtime','totaltime',
'jultime', 'n', 'co2interc', 'co2slope',
'co2linr2','co2linp','co2stderr','co2slopeconf', 'n2ointerc', 'n2oslope',
'n2olinr2','n2olinp', 'n2ostderr', 'n2oslopeconf','ch4interc', 'ch4slope',
'ch4linr2','ch4linp', 'ch4stderr', 'ch4slopeconf','nh3interc', 'nh3slope',
'nh3linr2','nh3linp','nh3stderr','nh3slopeconf','interftemp','airpressure','h
2o','IFGheight'])

            preflushsec=float(pretimeentry.get())
            sampletimesec=float(sampletimeentry.get())*60

            # molardensity = gram/liter, CO2 is 44gram/mol -> 1 mol is about 22
liter (gas law) -> 44/22-> ~2 gram CO2/ liter
            n2omolardensitycorr=1.9634*(273/(273+temperature))
            co2molardensitycorr=1.9635*(273/(273+temperature))
            ch4molardensitycorr=0.7158*(273/(273+temperature))

```



```

nh3molardensitycorr=0.7598*(273/(273+temperature))
n2oconv=0.549993
co2conv=0.235798773
ch4conv=0.646856
nh3conv=0.8225

#slope=ppm/s
#ppm/sec=(ul/l)/s
#liters and seconds is known, calculate ml->ng
# ppm*volume(liter)=total ul of gas of interest in system
# ul*molardensity = ug of gas of interest
# ug*conversion = ug of element of interest
# SO: (ppm n2o/second)*totalvolume*n2omolardensitycorr*n2oconv = ug N/s
# SO: (ppm n2o/second)*totalvolume*n2omolardensitycorr*n2oconv/soilarea
= ug N/(s*m2)

row=0
while row < amountrows :
    row2=row
    port=ftirdata['Line'][row]
    print "port: " + str(port)
    firsttime=ftirdata['Epoch'][row]
    nextport=port
    while nextport==port :
        row2=row2+1
        if row2+1 > amountrows:
            break
        nextport=ftirdata['Line'][row2]
        lasttime=ftirdata['Epoch'][row2-1]
        totaltimeport=lasttime-firsttime
        avgtimeepoch=(lasttime+firsttime)/2

julday=datetime.datetime.utcnow().timestamp().strftime("%j")
avgtime=datetime.datetime.utcnow().timestamp().strftime("%H:%M")
hour=float(datetime.datetime.utcnow().timestamp().strftime("%H"))
minute=float(datetime.datetime.utcnow().timestamp().strftime("%M"))
floattime=float(hour)/24+float(minute)/(24*60)
jultime=float(julday)+floattime
print "flux measurement start: " + str(jultime)

if totaltimeport > preflushsec+sampletimesec and port<32:
    print "enough data for port: " +str(port)
    chamberoffset=chamberoffsetlist[port-1];
    if jultime>offsetchange1:
        print "using offsetlist1"
        chamberoffset=chamberoffsetlist1[port-1]
    if jultime>offsetchange2:
        print "using offsetlist2"
        chamberoffset=chamberoffsetlist2[port-1]
    offsetcorrectedvolume=totalvolume+chamberoffset/10*soilarea*100
    row3=row
    x=[]; yh2o=[]; yco2ppm=[]; yn2oppm=[]; ynh3ppm=[]; ych4ppm=[]
    yIFGh=[]; listinterftemp=[]; listairpressure=[];

```

```

temptime=firsttime
while temptime < lasttime :
    if temptime > firsttime+preflushsec and temptime <
firsttime+preflushsec+sampletimesec :
        x.append(ftirdata['Epoch'][row3]-ftirdata['Epoch'][row]-
preflushsec)
        yh2o.append(ftirdata['Water_vapor_H2O'][row3])
        yco2ppm.append(ftirdata['Carbon_dioxide_CO2'][row3])
        yIFGh.append(ftirdata['IFG_peak_height'][row3])
        yn2oppm.append(ftirdata['Nitrous_oxide_N2O'][row3])
        ych4ppm.append(ftirdata['Methane_CH4'][row3])
        ynh3ppm.append(ftirdata['Ammonia_NH3'][row3])
        listairpressure.append(ftirdata['Ambient_pressure'][row3])

listinterftemp.append(ftirdata['Interferometer_temperature'][row3])
row3=row3+1
temptime=ftirdata['Epoch'][row3]

avginterftemp=np.mean(listinterftemp)
avgairpressure=np.mean(listairpressure)
avgh2o=np.mean(yh2o)
avgIFGh=np.mean(yIFGh)
co2slope, co2linintercept, co2linr, co2linp, co2std_err =
stats.linregress(x,yco2ppm)
n2oslope, n2olinintercept, n2olinr, n2olinp, n2ostd_err =
stats.linregress(x,yn2oppm)
ch4slope, ch4linintercept, ch4linr, ch4linp, ch4std_err =
stats.linregress(x,ych4ppm)
nh3slope, nh3linintercept, nh3linr, nh3linp, nh3std_err =
stats.linregress(x,ynh3ppm)
co2linr2=co2linr**2; n2olinr2=n2olinr**2; ch4linr2=ch4linr**2;
nh3linr2=nh3linr**2;
n=len(yn2oppm)

df=n-2.0
alpha=1.0-(float(confidence_interval)/100.0)
critical_prob=1.0-float(alpha)/2.0
t=stats.t.ppf(critical_prob,df)

n2oslopeconf=float(t)*n2ostd_err*offsetcorrectedvolume/soilarea*n2omolardensi
tycorr*n2oconv

co2slopeconf=float(t)*co2std_err*offsetcorrectedvolume/soilarea*co2molardensi
tycorr*co2conv

ch4slopeconf=float(t)*ch4std_err*offsetcorrectedvolume/soilarea*ch4molardensi
tycorr*ch4conv

nh3slopeconf=float(t)*nh3std_err*offsetcorrectedvolume/soilarea*nh3molardensi
tycorr*nh3conv

if doHMRfit.get(>0):
    n2oHMRslope,n2oHMRintercept,n2oHMRmixratio=doHMR(x, yn2oppm)
    co2HMRslope,co2HMRintercept,co2HMRmixratio=doHMR(x, yco2ppm)
    ch4HMRslope,ch4HMRintercept,ch4HMRmixratio=doHMR(x, ych4ppm)

```

```

nh3HMRslope,nh3HMRintercept,nh3HMRmixratio=doHMR(x, ynh3ppm)
if n2oHMRslope !='NA': n2oslope=n2oHMRslope
if co2HMRslope !='NA': co2slope=co2HMRslope
if ch4HMRslope !='NA': ch4slope=ch4HMRslope
if nh3HMRslope !='NA': nh3slope=nh3HMRslope

n2oslope=n2oslope*
offsetcorrectedvolume/soilarea*n2omolardensitycorr*n2oconv
co2slope=co2slope*
offsetcorrectedvolume/soilarea*co2molardensitycorr*co2conv
ch4slope=ch4slope*
offsetcorrectedvolume/soilarea*ch4molardensitycorr*ch4conv
nh3slope=nh3slope*
offsetcorrectedvolume/soilarea*nh3molardensitycorr*nh3conv

resultswriter.writerow([port,ftirdata['Epoch'][row],julday,avgtime,totaltimemp
ort, jultime, n, co2linintercept,co2slope,
co2linr2,co2linp,co2std_err,co2slopeconf, n2olinintercept, n2oslope,
n2olinr2, n2olinp,n2ostd_err,n2oslopeconf, ch4linintercept, ch4slope,
ch4linr2,ch4linp, ch4std_err, ch4slopeconf, nh3linintercept, nh3slope,
nh3linr2,nh3linp,nh3std_err,nh3slopeconf,avginterftemp,avgairpressure,avgh2o,
avgIFGh])

if dosavetopdf.get()>0:
# save fluxes to file
fig = P.figure(figsize=(16, 16))
x = numpy.array(x)
y1 = numpy.array(yco2ppm)
y2 = numpy.array(yn2oppm)
y3 = numpy.array(ych4ppm)
y4 = numpy.array(ynh3ppm)
(m,b)=P.polyfit(x,y1,1)
y12 = P.polyval([m,b],x)
(m,b)=P.polyfit(x,y2,1)
y22 = P.polyval([m,b],x)
(m,b)=P.polyfit(x,y3,1)
y32 = P.polyval([m,b],x)
(m,b)=P.polyfit(x,y4,1)
y42 = P.polyval([m,b],x)

if doHMRfit.get()>0:
xHMR = linspace(x.min(), x.max(), 100)
#c0, fluxppmmin, mixratio
fitfunc = lambda p, xHMR: p[0]+p[1]*((1.0-p[2])**xHMR-
1.0)/p[2] # Target function

line1=fig.add_subplot(411)
line1.scatter(x, y1)
line1.plot(x, y12)
if doHMRfit.get()>0 and co2HMRslope!='NA':
p1=numpy.array([float(co2HMRintercept),-
float(co2HMRslope),float(co2HMRmixratio)])
line1.plot(xHMR, fitfunc(p1, xHMR)) # Plot the HMR fit
line1.grid()
line1.set_title('Port: '+str(port)+' time: '+str(jultime))
line1.set_ylabel('CO2 concentration (ppmv)', color='b')

```

```

line1.set_xlabel('time (seconds)', color='b')

line2=fig.add_subplot(412)
line2.scatter(x, y2)
line2.plot(x, y22)
if doHMRfit.get()>0 and n2oHMRslope!='NA':
    p1=numpy.array([float(n2oHMRintercept),-
float(n2oHMRslope),float(n2oHMRmixratio)])
    line2.plot(xHMR, fitfunc(p1, xHMR)) # Plot the HMR fit
line2.grid()
line2.set_ylabel('N2O concentration (ppmv)', color='b')
line2.set_xlabel('time (seconds)', color='b')

line3=fig.add_subplot(413)
line3.scatter(x, y3)
line3.plot(x, y32)
if doHMRfit.get()>0 and ch4HMRslope!='NA':
    p1=numpy.array([float(ch4HMRintercept),-
float(ch4HMRslope),float(ch4HMRmixratio)])
    line3.plot(xHMR, fitfunc(p1, xHMR)) # Plot the HMR fit
line3.grid()
line3.set_ylabel('CH4 concentration (ppmv)', color='b')
line3.set_xlabel('time (seconds)', color='b')

line4=fig.add_subplot(414)
line4.scatter(x, y4)
line4.plot(x, y42)
if doHMRfit.get()>0 and nh3HMRslope!='NA':
    p1=numpy.array([float(nh3HMRintercept),-
float(nh3HMRslope),float(nh3HMRmixratio)])
    line4.plot(xHMR, fitfunc(p1, xHMR)) # Plot the HMR fit
line4.grid()
line4.set_ylabel('NH3 concentration (ppmv)', color='b')
line4.set_xlabel('time (seconds)', color='b')
pdffile.savefig(dpi=150)
P.close()

else :
    print "missing data for port: " +str(port)
    row=row2

openinputfile.close()
openresultsfile.close()
if dosavetopdf.get()>0:
    pdffile.close()

def doHMR(xHMR,yHMR):
    # # _____ franks interest model(==HMR in different
form)_____
    # # linear regression
    linslope, linintercept, linr, linp, std_err = stats.linregress(xHMR,yHMR)
    linr2=linr**2
    ##c0, fluxppmmin, mixratio
    fitfunc = lambda p, xHMR: p[0]+p[1]*((1.0-p[2])**xHMR-1.0)/p[2] # Target
function
    errfunc = lambda p, xHMR, yHMR: fitfunc(p, xHMR) - yHMR # Distance to the
target function

```

```

    p0 = [float(yHMR[0]),float(linslope) , 0.0003] # Initial guess for the
parameters
    p1, success = optimize.leastsq(errfunc, p0[:], args=(xHMR, yHMR))
    HMRintercept=p1[0]
    HMRslope=-p1[1]
    mixratio=p1[2]

    if (success==FALSE or mixratio<0 or mixratio>0.003):
    #if (success==FALSE ):
        results=numpy.array(['NA','NA','NA'])
        #print "HMR failed"
    else:
        #print "HMR succes"
        results=numpy.array([HMRslope,HMRintercept,mixratio])
        #print results
    return results
#
-----
#-----GUI-----
-----
#
-----

# create a root TkInter frame
root = Tk()
root.title('FTIR flux calculator 20160531')

# _____ LOGO&TITLE _____
-----

uofslogo = PhotoImage(file="uofs.gif")
logo=Label(root, anchor=E, image=uofslogo, bg='darkgreen')
bigtitle = Label(root, anchor=W, font=('times', 20, 'bold'),
fg='white',bg='darkgreen', text="FTIR flux calculator ")
logo.grid(row=0,column=3,columnspan=1,sticky=[N,S,E,W])
bigtitle.grid(row=0,column=0,columnspan=3,sticky=[N,S,E,W])

# _____ OPTIONS _____
-----

optionstitle = Label(root, anchor=W, font=('times', 12, 'bold'),
text="options:")
optionstitle.grid(row=1,column=0, columnspan=3, sticky=[N,S,E,W])

pretimeentrytitle = Label(root, anchor=W, text="pre-flushing time (s):")
pretimeentrytitle.grid(row=3,column=0, columnspan=1, sticky=[E])
pretimeentry= Entry(root,width=4)
pretimeentry.insert(0,"150")
pretimeentry.grid(row=3,column=1, columnspan=1, sticky=[W])

sampletimeentrytitle = Label(root, anchor=W, text="sampling time for linreg
(min):")
sampletimeentrytitle.grid(row=4,column=0, columnspan=1, sticky=[E])
sampletimeentry= Entry(root,width=4)
sampletimeentry.insert(0,"11.5")
sampletimeentry.grid(row=4,column=1, columnspan=1, sticky=[W])

```

```

dosavetopdf=IntVar()
savetopdfapply = Checkbutton(root, text="save individual fluxes to pdf",
variable=dosavetopdf)
savetopdfapply.grid(row=11,column=0, columnspan=5, sticky=W)

doHMRfit=IntVar()
doHMRapply = Checkbutton(root, text="Fit the exponential HMR model",
variable=doHMRfit)
doHMRapply.grid(row=12,column=0, columnspan=5, sticky=W)

doUnits=IntVar()
doUnitsapply = Checkbutton(root, text="Write units in datafile",
variable=doUnits)
doUnitsapply.grid(row=13,column=0, columnspan=5, sticky=W)

# _____ CALC INDIVIDUAL
# FLUXES
f0=Frame(root,height=1, width=450, bg="grey")
f0.grid(row=24,column=0, columnspan=4, pady=5,sticky=S)

calcfluxtitle = Label(root, anchor=W, font=('times', 12, 'bold'),
text="Calculate fluxes")
calcfluxtitle.grid(row=25,column=0, columnspan=4, sticky=[N,S,E,W])
calcfluxhelp = Label(root, anchor=W, text="Open a Calcmets results file")
calcfluxhelp.grid(row=26,column=0, columnspan=4, sticky=[N,S,E,W])
calcfluxhelp2 = Label(root, anchor=W, text="input concentrations in ppmv
(=ul/l)")
calcfluxhelp2.grid(row=27,column=0, columnspan=4, sticky=[N,S,E,W])

buttonopenconcfile=Button(root, text='open calcmets results file',
command=askopenresultsfilename)
buttonopenconcfile.grid(row=28,column=1,columnspan=1,sticky=[W])
calcfluxhelp3 = Label(root, anchor=W, text="results are saved in ug
CorN/(m2*s)")
calcfluxhelp3.grid(row=29,column=0, columnspan=4, sticky=[N,S,E,W])

#
# _____
root.mainloop( )

```