Nitrous Oxide Emissions in Southern Alberta Croplands in response to Nitrogen Rates, Fertigation and Moisture

by

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Abstract

Irrigated agriculture is an important source of global food supply due to its high production intensity; however, it is also a large user of water and nitrogen fertilizer, and therefore, a potential large contributor of N_2O emissions. This study explores the viability of fertigation, a method of splitting N fertilizer by using existing irrigation equipment to apply in-crop applications of N added with irrigation water, as a means to reduce N_2O emissions. This field study examined N fertilizer rates of 0, 60, 90 or 120 kg N ha^{-1} in wheat and canola crops applied once at seeding versus split N application using in-crop fertigation (i.e., fertilizer applied at two timings throughout the growing season: once at seeding at 30, 60 or 90 kg N ha^{-1} plus 30 kg N ha^{-1} through fertigation done at wheat tillering or canola 5-leaf growth stages in early June) in Southern Alberta during two experimental years (2015 and 2016). The cumulative emissions from weekly gas measurements revealed that N_2O emissions, on a per-area and per-yield basis, were directly related to N fertilizer rates. When examining the effects of fertigation to split the N application, we found that canola was unaffected, however, at intermediate rates (60 and 90 kg N ha^{-1}), fertigation effectively reduced N_2O emissions by half in the wheat crop in 2016. These results suggest that lower N rates at crop seeding reduce the availability of N substrate in the soil early in the growing season when plant uptake is still low, thereby reducing the risk of N transformation to N_2O. The use of fertigation to apply N later in the growing season, when plant N demand and uptake is relatively high, could lead to a better use of fertilizer compared to a one-time application in the early spring. These effects were amplified when high soil moisture in the early spring was coupled with higher seeding N fertilizer rates which led to even higher rates of N_2O production. A laboratory incubation of the 2016 wheat treatments reinforced the principle that available N was associated with N_2O production. An in-depth examination of the 90 and 120 kg ha^{-1} total N treatments showed that higher initial concentrations of nitrate in the incubation soils was highly correlated to the amount of N_2O produced over a 32-day incubation. However, the cumulative N_2O emissions in soil taken from the fertigation 90 kg N ha^{-1} rate treatment had contradictory results to those seen in the field, larger amounts of N_2O were produced from fertigated compared to the unfertigated microcosms. This was a result of the higher concentration of N in the soil following the recent fertigation (applied 9 days prior to field sample collection). However, this difference in nitrate concentration was not detected at the higher 120 kg N ha^{-1} rate and may have been a result of the differences in the sizes of the plant nutrient sink; larger plants from the higher fertilizer rate plots were able to take up the additional N applied through fertigation. Moisture treatments that simulated a typical range of irrigated conditions were also imposed on the incubated soils but did not significantly affect the production of N_2O. More extreme moisture fluctuations (higher moisture for prolonged periods simulating irrigation and early-season rainfalls) should be explored to determine the effect of intense irrigation regimes or weather patterns on N_2O emissions.

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Table of Contents

List of Tables

List of Figures

1. General Introduction

Greenhouse gases (GHGs) absorb and re-emit long-wave radiation from the earth back to the surface which increases the average global temperature and contributes to global climate change (Kebreab et al., 2006). The three GHGs are carbon dioxide, methane and nitrous oxide (N_2O). Nitrous oxide is an important GHG due to its high global warming potential, which is 298 times larger than that of carbon dioxide, and because it also contributes to the depletion of the ozone layer (Myher et al., 2013). Also, it is an important GHG in cropping agriculture due to the large proportion of N_2O produced in these systems; in Canada, the agricultural sector is responsible for 70% of anthropogenically produced N_2O emissions which are highly influenced by the use of synthetic fertilizers; N_2O emissions increase in direct proportion to the amount of N fertilizer applied (Johnson et al., 2007). Nevertheless, N fertilizer use in the Canadian Prairies has been increasing due to its correlated effect on increasing crop yields (Giweta et al., 2017) causing even greater emissions of N_2O in agriculture. Crop irrigation, another management technique, can also contribute to the amount of N_2O produced in cropping systems; irrigation increases soil moisture by applying additional water above natural rainfall which in turn increases soil moisture, increases microbial activity and causes higher production of N_2O (Trost et al., 2013). Irrigation is prevalent in Southern Alberta, with the area of land using irrigation increasing from approximately 400 000 acres in 1975 to over 690 000 acres in 2016 (AAF, 2016). Nitrogen fertilization and irrigation use are important to agricultural production in Southern Alberta but management options are needed to reduce the impact of N_2O emissions and maintain a sustainable agricultural system.

The two main microbial processes attributed to N_2O gas production are nitrification and denitrification (Firestone and Davidson, 1989). Nitrification generally occurs in aerobic conditions and involves the oxidation of ammonium (NH_4^+) to hydroxylamine (NH_2OH), nitrite (NO_2^-), or nitrate (NO_3^-) with N_2O as a byproduct of this process (Bremner, 1997; Farquharson and Baldock, 2008, Butterbach-Bahl et al., 2013). Denitrification generally occurs under anaerobic conditions and is the reduction of NO_3^- to NO_2^-, nitric oxide (NO), N_2O and dinitrogen (N_2) (Bremner, 1997; Farquharson and Baldock, 2008). Although both processes result in N_2O production, large pulses of N_2O are usually attributed to denitrification, which are largely dependent on high soil moisture and can increase due to abundant rainfall or irrigation (Butterbach-Bahl et al., 2013). The substrates required for nitrification and denitrification are made available through mineralization of organic N into NH_4^+ or through the hydrolysis of urea into NH_4^+ (Farquharson and Baldock, 2008). Additional N can be applied in cropping systems through the use of fertilization.

To apply fertilizers to crops, fertigation can be used. Fertigation is a management technique which employs conventional irrigation equipment to apply N fertilizers to crops by mixing water soluble fertilizers into irrigation water (Fentabil et al., 2016). The implementation of fertigation has been proposed as a management technique that could reduce the production of N_2O by splitting the application of N fertilizer. Split application through fertigation is possible because the fertigation water can be applied to already growing crops since the sprinklers do not damage plants; fertigation can be split applied with additions occurring later in the growing season to better match N application with plant uptake thus reducing excess N in the soil (Grant et al., 2012). Less N in the soil means there are less opportunities for N loss through ammonia volatilization, leaching or emissions of N_2O or dinitrogen gas (Grant et al., 2012). Fertigation can be a technique that not only reduces harmful N_2O emissions through split applications, but also a method of increasing the efficiency of N fertilizers by reducing other N losses in the soil.

However, the use of irrigation to apply fertilizer also increases soil moisture, which coupled with the inherent increase of N in the soil, may lead to pulses of N_2O production not normally seen with conventional fertilization.

There has been little research done concerning the effects of sprinkler-applied N fertilizer (Liu et al., 2011) while only a few studies have observed the effects using drip applicators (Abalos et al., 2014; Fentabil et al., 2016a; Fentabil et al., 2016b; Kennedy et al., 2013; Trost et al., 2014), and although there are some studies documenting the effect of extreme wetting and drying cycles on N_2O production (Beare et al., 2009; Borken and Matzner, 2009; Ruser et al., 2006), there is little research on the effects of splitting N applications coupled with different moisture regimes that resembled irrigation conditions. Therefore, this thesis aims to i) to determine how N fertilizer rate in common annual crops [wheat (*Triticum aestivum*) and canola (*Brassica napus*)] using N application all at once at crop seeding versus in-crop fertigation plus N applied at seeding can impact N_2O emissions in both a field and controlled laboratory setting; ii) to estimate the yield-scaled emissions and the emission factors of N_2O from wheat and canola fields as functions of N fertilizer rate and fertigation; iii) to examine temporal relationships between irrigation and rainfall patterns versus N_2O fluxes under various N rates, N timing and fertigation; and iv) to determine if varying soil moisture regimes affect N_2O emissions across a range of N managements in Southern Alberta.

2. Nitrous Oxide Emissions from Wheat and Canola Fields in Southern Alberta: Fertigation and Nitrogen Rate Effects

2.1 Abstract

The increased use of synthetic nitrogen fertilizers in agriculture is contributing to the amount of nitrous oxide (N_2O) being produced and released into the atmosphere. N_2O is not only a potent greenhouse gas which contributes to global warming, but it is also a major contributor to the deterioration of the ozone layer. The use of fertigation, which is the process of splitting the application of N fertilizer through the implementation of irrigation equipment, is being researched as a potential means of reducing agricultural N_2O emissions. This field study examined N fertilizer rates of 0, 60, 90 or 120 kg N ha^{-1} in wheat and canola crops using conventional fertilization (i.e., granular, side-banded urea applied at seeding at 0, 60, 90 or 120 kg N ha^{-1}) versus split N application using in-crop fertigation (i.e., fertilizer applied at two times during the growing season: once at seeding at 30, 60 or 90 kg N ha^{-1} plus 30 kg N ha^{-1} through fertigation at wheat tillering or canola 5-leaf growth stages in early June) in Southern Alberta during two experimental years (2015 and 2016). Consistent with previous studies, N_2O emissions, on a per-area and per-yield basis, were directly related to N fertilizer rates. Likewise, our emission factor (EF) estimates indicated that lowering N rates particularly at crop seeding can reduce N_2O emissions. When examining the effects of splitting N via fertigation, we found that N_2O emissions from canola fields were unaffected by fertigation. However, when wheat received intermediate N rates (total doses of 60 and 90 kg N ha^{-1}), and early season rainfalls took place (May 2016), fertigation effectively reduced N_2O emissions by half, likely because of favorable growing conditions and input timing for crop uptake of N. These results suggest that the N_2O mitigation effect of fertigation is crop- and weather-specific. The largest differences in daily N_2O fluxes consistently occurred across N treatments within one and three weeks after the

urea application at seeding. This indicates that high N fertilizer rates added at seeding exceed early plant needs, and hence, this approach increased the risk for N_2O losses in May provided that wet field conditions occurred.

2.2 Introduction

Nitrous oxide (N_2O) is a greenhouse gas (GHG) that has a global warming potential 298 times greater than carbon dioxide and contributes to the depletion of stratospheric ozone (Myhre et al., 2013). In Canada, agriculture accounts for 70% of the anthropogenically produced N_2O (Kebreab et al., 2006) and the use of synthetic nitrogen fertilizers in agriculture contributes significantly to this amount (Johnson et al., 2007) however, the increased yield potentials in wheat and canola crops has been correlated to greater fertilizer use by producers and leads to higher rates of N_2O production (Giweta et al. 2017).

The main microbial processes contributing to N_2O production are nitrification and denitrification (Firestone and Davidson, 1989). Nitrification is an aerobic process in which ammonium (NH_4^+) is oxidized to hydroxylamine (NH_2OH), nitrite (NO_2^-), or nitrate (NO_3^-) while denitrification occurs in anaerobic conditions and is the reduction of NO_3^- to NO_2^-, nitric oxide (NO), N_2O and dinitrogen (N_2) (Bremner, 1997; Farquharson and Baldock, 2008). N_2O production during nitrification occurs when NO_2^- or NH_2OH are oxidized (Butterbach-Bahl et al., 2013). However, recent research has found that both nitrification and denitrification processes do not necessarily occur only in aerobic and anaerobic conditions, respectively (Hernandez-Ramirez et al., 2009; Stevens et al., 1997; Wolf and Russow, 2000), but rather these N transformations can take place simultaneously regardless of oxygen status making it difficult to partition nitrification and denitrification sourced N_2O. Major pulse emissions of N_2O are usually attributed to denitrification, which are largely dependent on discrete events triggered by increases soil water due to abundant rainfall or irrigation (Butterbach-Bahl et al., 2013). Along with soil water, other controlling factors on soil processes associated with N_2O fluxes include temperature, mineral N concentrations, organic matter, aeration, texture, and pH (Butterbach-Bahl et al., 2013; Dobbie et al., 1999; Jamali et al., 2016).

Fertigation is a management technique which implements conventional irrigation equipment to apply N fertilizers to crops by mixing water soluble fertilizers into irrigation water (Fentabil et al., 2016). The fertigation water can be applied at any time during crop growth because the water is sprayed onto the crops at intensities that do not damage the plant. This allows producers to split and schedule fertilizer inputs into multiple in-season applications which may hypothetically reduce N_2O emissions because fertigation can be used to apply N to match more closely the time when plants require nutrients (Grant et al., 2012). Synchronizing fertilizer application to plant uptake is important because the mineral nitrogen present in the soil, if it is not taken up by plants, is vulnerable to immobilization or losses through ammonia volatilization, nitrate leaching or emissions of N_2O or dinitrogen gas (Grant et al., 2012); therefore, it is ideal to limit the N input and available N in the soil until the crop requires it, reducing the risk of losses that are detrimental to the environment. However, fertigation could also simultaneously increase the concentration of N and water in the soil, and may increase the risk of N_2O emissions by creating ideal conditions for denitrification (Fentabil et al., 2016a; Zebarth et al., 2008). It is unknown if the benefits of split N applications outweigh the disadvantages of the increased pulse of mineral N and high water-filled pore space (WFPS) inherent with fertigation. Also, there have been very few studies examining the effects of fertigation coupled with regular irrigation using sprinkler applicators. Moreover, to date, most of the available literature on fertigation effects focused on using drip irrigation (Abalos et al., 2014; Fentabil et al., 2016a; Fentabil et al., 2016b; Kennedy et al., 2013; Trost et al., 2014).

To test the effects of N fertilizer rates and sprinkler fertigation on N_2O production, a study was conducted in 2015 and 2016 in wheat (*Triticum aestivum*) and canola (*Brassica napus*) replicated plots near Lethbridge, Alberta, Canada. Nitrogen fertilizer was either added once at seeding or split between seeding and an early growth stage using fertigation. The objectives of this study were: i) to determine how N fertilizer rate impacts N_2O emissions, ii) to determine how splitting the total N fertilization into application at seeding and in-crop fertigation affects the N_2O emitted when compared with applying the total N rate at seeding, iii) to estimate the yield-scaled emissions and the emission factors of N_2O from wheat and canola fields as functions of N fertilizer rate and fertigation, and iv) to examine temporal relationships between irrigation and rainfall patterns and N_2O fluxes in wheat and canola fields under various N rates and fertigation.

2.3 Materials and Methods

2.3.1 Site Description and Experimental Design

The research plots were established east of the city of Lethbridge, Alberta at the Alberta Agriculture and Forestry Research Centre (49.41218° N, 112.45172° W). The study was conducted over two consecutive growing seasons (2015 and 2016) in adjacent sections of the research farm each year. Soils at this site are moderately fine-textured Chernozems developed on water-lain sediments. Soil properties for the field site were determined using soil samples taken in spring 2016. The soil had a sandy clay loam to loam texture (457 g kg^{-1} sand, 285 g kg^{-1} silt, 258 g kg^{-1} clay as determined by hydrometer method), a bulk density of 1.49 g cm^{-3}, organic carbon concentration of 20.4 g C kg^{-1} soil, total nitrogen of 1.6 g N kg^{-1} soil, and a C:N ratio of 13. The site has a 30-year average (1971-2000) annual precipitation of 386.3 mm and annual average temperature of 5.7 °C (Environment Canada 2017).

For both wheat (*Triticum aestivum* cv. Carberry) and canola (*Brassica napus* cv. VR9562 in 2015 and 74-44 BL in 2016) crops (seeded into canola stubble), a blocked, split-plot design was applied with the fertigation treatment as the main plot (fertigation or no fertigation) with different nitrogen fertilizer rates applied during seeding at the sub-plot level. N_2O emissions and other response variables for this investigation were measured on the following fertilizer treatments: 60, 90 and 120 kg N ha^{-1} added at seeding in early May (no fertigation), and 30, 60 and 90 kg N ha^{-1} added at seeding plus another 30 kg N ha^{-1} added through fertigation in early June during the tillering (wheat) or 5- leaf (canola) growth stages. To make comparisons between the fertigation treatments, the total N rate of the applied fertilizer equaled 60, 90 or 120 kg N ha^{-1} during the entire growing season. Controls with no fertilizer were also evaluated. It should be noted that the seven treatments of our study were a subset of the treatments selected from a larger study which encompassed eight N rates in combination with three timings of in-crop fertigation with a total of 30 treatments for both crops (please see Appendix A for details). The treatments in our study were chosen to test the effects at median rates which are common to those already used in Southern Alberta for wheat and canola (Alberta Agriculture and Forestry, 2017) while the tillering and 5-leaf stage for fertigation timing was chosen to test the most beneficial timing of fertilizer application for plant uptake and the optimal time to reduce N_2O emissions during peak crop uptake.

Each crop occupied four blocks, two were fertigated and two were not (Appendix A). For each crop, the three fertigation treatments were replicated twice in two blocks for a total of 12 fertigation treatments and the four no fertigation treatments were also replicated twice in two blocks for a total of 16 no fertigation treatments. A total of 56 chambers were used for the canola and the wheat crops. The chambers were located at least 2.3 m from the edges of the block to avoid any edge effects and to act as a buffer for fertigation treatments. Two additional replicated plots within each block measuring 2.3 m by 7 m were used to measure plant grain yield. The fertilizer added at seeding was granular urea (side banded 3 to 5 cm from the seed and 0 to 2.5 cm deep) while liquid urea-ammonium nitrate (UAN) was used for fertigation and applied at a rate of 30 kg N ha^{-1} at the tillering stage for wheat or at the 5-leaf stage for canola as part of a 12 mm irrigation application. A calibrated fertilizer injection pump was used to add UAN to the lateral roll sprinkler irrigation system which then passed over the experimental area and applied fertigation water only to the specified treatment areas. The system was flushed with regular water and passed back over the experimental area and applied 12 mm of regular water to the plots which had not been fertigated. The irrigation water was sourced from the St. Mary River Irrigation System and was applied throughout the growing season to all treatment plots in equal amounts to ensure that water was not yield limiting. In 2015 seeding and granular urea application occurred on 29 April, fertigation was applied on 8 June and harvest was on 27 August. In 2016 seeding and granular urea application occurred on 5 May, fertigation was applied on 7 June and harvest occurred on 30 August.

2.3.2 Gas Sampling and Analysis

The nonsteady-state chamber method (Rochette and Bertrand 2008) was used to measure N_2O gas fluxes. Rectangular chambers (64.1 cm × 15.6 cm × 15 cm) consisted of a chamber body and a detachable lid with a rubber septum. Chambers bodies were installed on each plot (n=56) after seeding and granular fertilizer application in 2015 and 2016 perpendicular to the crop rows and to a depth of 5 cm in the middle of each chamber plot. During installation, a small knife or trowel was used to dig a narrow trench the diameter of the frame and care was taken not to disturb the soil on the inside of the trench. The chamber body was then buried 5 cm deep in the trench to create a head space of 10 L within the chamber. During gas sampling, lids were placed over the chamber bodies to create a closed chamber and the crop was bent into the chamber until this was no longer practical, after which the crop was cut. Gas samples were taken at least once a week throughout both growing seasons, 21 times in 2015 between 30 April and 15 October and 25 times in 2016 between 6 May and 17 October. Flux sampling was conducted two times per week in the weeks following key field events including irrigation, fertilization, fertigation or heavy rain. To ensure consistency in the flux estimation, the gas samples were taken between 9 am and 3 pm. On each sampling day, every chamber was sampled at 15, 30 and 45 minutes after securing the lids on the chamber bodies. Ambient samples were also taken each sampling day at a height of 10 cm above ground to represent time zero. A pair of ambient air samples was taken twice in 2015, once at "time zero", when the first lid was placed on the first chamber body and another pair taken just after the third sampling of the 14th chamber. In 2016, more ambient samples were taken: 1 when the lid went on the first chamber body, 1 just after the first sampling of the first chamber, 1 just after the first sampling of the 14th chamber, 1 just after the second sampling of the 14th chamber, and 1 just after the third sampling of the 14th chamber with 4 replicates which equated to 20 ambient samples for each sampling day. Air temperature at the start and end of sampling was recorded from the Lethbridge Research Farm Weather Station located about 800 m south east of the experimental site.

To collect the gas sample, a 20 mL syringe was flushed twice with ambient air then inserted into the rubber septum on the chamber lid where it was flushed twice with air from inside the closed chamber. A 20 mL sample was then pulled into the syringe then transferred into an evacuated 10 mL exetainer (Labco, UK). Samples were analyzed for concentrations using a gas chromatograph (Thermo Fisher Scientific Trace 1310 Gas Chromatography) and an autosampler (CTC Analytics Combi PAL auto sampler) equipped with an electron capture detector to measure N_2O. Minimum analytical detectable N_2O flux using this instrumentation has been estimated as 0.088 ppmv (Lin *et al.*, in press).

The daily N_2O flux of each chamber was determined by fitting a linear or quadratic curve between the average ambient N_2O measurement from that day along with the three N_2O measurements from the chamber versus time (Lin *et al.*, in press). A test was performed to determine the existence of outliers for each flux calculation by finding the lowest R^2 value with each combination of 3 of the 4 fluxes. If an outlier was found this value was removed and the flux calculation was performed using 3 values instead of 4. Using an alpha value of 0.20, zero flux was determined if there was no significant relationship. If the relationship was significant, the modified ideal gas law was used to calculate the flux. The equation used was:

$$N_2O\ Flux = \frac{S \times P \times V \times A^{-1}}{R \times T} \qquad [1]$$

where N_2O flux is the flux rate of N_2O (μmol min^{-1} m^{-2}); S is the slope of the line from either the simple linear regression or the first-order derivative at time zero from the quadratic curve (μL L^{-1} min^{-1}) (Pennock et al., 2010; Yates et al., 2006); P is the gas pressure (atm); V is the volume of the chamber (L); A is the surface area of the chamber (m^2); R is the gas constant (atm μL K^{-1} $μmol^{-1}$) and T is the temperature of the gas (K). In 2015, we recorded that the wheat fluxes were 69, 6 and 26% linear, quadratic and zero regressions, respectively and that in canola the fluxes were 71, 7 and 22% linear, quadratic and zero regressions, respectively. While in 2016, we recorded the wheat fluxes were 58, 9 and 33% linear, quadratic and zero regressions, respectively and the canola fluxes were 54, 6 and 39% linear, quadratic and zero regressions, respectively. To calculate the cumulative emissions between two consecutive sampling dates, the product of the average N_2O flux rate and the time interval between the two sampling dates was used.

2.3.3 Soil Sampling and Analysis

Soil sampling was conducted to determine soil physical and chemical properties before and after fertilizer applications at the field site. Soil samples were taken four times within the 2015 growing season (at pre-seeding on 14 April, 4 days before fertigation application on 4 June, 10 days after fertigation application on 18 June, and after crop harvest on 28 August) and five times within 2016 (at pre-seeding on 19 April, after seeding on 15 May, 4 days before fertigation application on 3 June, 10 days after fertigation application on 17 June, and after crop harvest on 31 August). Each sample was composited from 4 random samples taken from the 0-15 cm soil depth increment using hand shovels. The pre-seeding and harvest soil samples were composites taken from each of the main fertigation or no fertigation treatment blocks and were analyzed for NH_4-N, NO_3-N, organic carbon, total nitrogen and particle size. The growing season soil samples were taken from each treatment sub plot (no samples were taken from the 90 kg N ha^{-1} treatments) and were analyzed for NH_4-N and NO_3-N. Concentrations of NH_4-N and NO_3-N were measured on 2M KCl extract (10:1), organic carbon and total nitrogen was determined using the dry combustion method.

To measure soil bulk density, undisturbed soil samples were taken from the wheat plots receiving 0, 90 and 120 kg N ha^{-1} with no fertigation as well as 60, 90 kg N ha^{-1} fertigation plots in June 2016. Samples were taken from the 5-10 cm depth. The top 5cm of the soil profile was excavated using a shovel to remove any plant litter and root material and to avoid soil surface crusting and excessive dryness. A metal soil core, 80 mm in diameter, was placed on the levelled soil surface and a sampler and hammer were used to insert the top of the core to the level of the exposed soil. The core was gently removed and both ends of the core were levelled using a knife before plastic covers were installed.

2.3.4 Grain Yield and Yield-based N_2O Emissions

Grain samples for this field experiment were not taken from the same plot as the chamber locations. Replicates of the same treatments were located in each block but were only used to gather biomass samples to avoid collecting material that had been disturbed by repeated gas sampling activities. The yield was measured in 2 plots within the same block and averaged to give each block/treatment combination one measurement for grain yield. All plots were straight cut on 27 August 2015 and 30 August 2016 with the combine harvester at less than 18% moisture content and the grain was dried at temperatures below 30 °C. Yield-based emissions were calculated by dividing the N_2O emission (g N ha^{-1}) from each experimental plot by the average dry matter grain yield (kg ha^{-1}) of the corresponding block/treatment combination.

2.3.5 N_2O Emission Factor

N_2O emission factor (EF) is a key metric used to calculate national inventories of greenhouse gas emissions (Rochette et al., 2008). To help develop a Tier II methodology [Intergovernmental Panel on Climate Change (IPCC), 1997] which can more accurately give estimations on a regional scale, it is useful to report N_2O emissions as a factor of applied N-fertilizer rate. In this experiment, the emission factor was calculated by subtracting the average cumulative N_2O emissions of the control treatment (which is assumed to be the background emission) from the average cumulative emissions of the treatment (60, 90 or 120 kg N ha^{-1}) then dividing by the total applied N rate:

$$Fertilizer\ N_2O\ EF\ (\%) = \frac{N_2O\ emission_{treatment} - N_2O\ emissions_{control}}{N\ fertilizer\ input} \qquad [2]$$

2.3.6 Statistical Analysis

The N_2O emission data was analyzed for daily and cumulative fluxes in both years and for both crops as separate data sets. A Shapiro-Wilk test was used to test for normality and the Bartlett test was used to determine homogeneous variance. If these assumptions were not met, a Box-Cox Power transformation was used to account for non-normality and Welch's analysis of variance (ANOVA) was used when variance was not homogeneous. As necessary, an offset of 2 or 3 was added to the N_2O emissions data for completing Box-Cox Power transformations. One-way ANOVAs and post hoc comparisons using Tukey's Honest Significant Difference (HSD) tests were used to assess the differences across total N rate, to determine differences in yield-based N_2O emissions and the differences between emission factors from the control. Similarly, two-way ANOVAs also followed by Tukey HSD were used to test the effects of fertigation and total N rate on cumulative N_2O emissions, yield-based N_2O emissions, the emission factor, to test for differences in cumulative N_2O emissions in different years and crops and to test for differences on high flux days. A confidence interval of 95% was used and all tests were done using R software, version 3.3.1.

2.4 Results

2.4.1 Wheat

2.4.1.1 Cumulative Area Based N_2O Fluxes

A one-way ANOVA conducted on non fertigated treatments indicated that there was no statistical significance of the total applied N rate on N_2O production in the wheat crop in 2015 but there was in 2016 (Table 2-1). In 2016, the amount of N_2O produced by the control (44.55 ± 40.05 g N_2O-N ha^{-1} $year^{-1}$) was significantly lower than N_2O production at both 90 kg N ha^{-1} (411.23 ± 135.32 g N_2O-N ha^{-1} $year^{-1}$) and 120 kg N ha^{-1} (374.04 ± 117.63 g N_2O-N ha^{-1} $year^{-1}$) but was not significantly different from N_2O production at 60 kg N ha^{-1} (249.39 ± 36.11 g N_2O-N ha^{-1} $year^{-1}$). Simple linear regressions were calculated to determine the relationship between N_2O production and total N rate for wheat. The linear regression in 2015 [N_2O emission (g N_2O-N ha^{-1}) = 339.68 + 2.44 x N rate; p=0.009; R^2 = 0.40] and 2016 [N_2O emission (g N_2O-N ha^{-1}) = 110.78 + 2.56 x N rate; p= 0.0008; R^2 = 0.56] both had positive relationships between N rate and N_2O production (Fig. 2-1a).

The fertigation treatment, which consisted of a 30 kg N ha^{-1} application of urea at seeding plus a 30 kg N ha^{-1} application of urea-ammonium nitrate at tillering, (an equivalent of 60 kg N ha^{-1} of added N) was compared to the non-fertigated treatment which received a total of 60 kg N ha^{-1} of urea at seeding etc. This was done to ensure that comparisons were only made between the emissions of plots which had equal total nitrogen added throughout the year. For the 2015 data, there was a significant effect of total N rate on N_2O production but HSD comparisons show that when treatments of equal total N are compared to each other, there were no significant differences in N_2O production at any of the rates (Table 2-1). For the 2016 data, there was a significant effect of total rate of nitrogen fertilizer and the use of fertigation on N_2O production (Table 2-1). At a total nitrogen rate of 90 kg N ha^{-1}, the fertigation treatment caused a significant reduction in N_2O emission of 47% compared to the corresponding non fertigated treatment. The other rates of fertilization, 60 and 120 kg N ha^{-1}, did not show significant differences in N_2O production as a function of N fertigation.

2.4.1.2 Yield-based N_2O Emissions

There was no significant effect of the total N rate on the yield-based N_2O produced in the wheat crop in 2015 (Table 2-1) however, there was a positive trend between total N rate and yield-based N_2O emissions [g N_2O-N emission per kg of grain =0.0525 + 0.0003 x N rate (kg N ha^{-1}); p=0.09; R^2 =0.37]. In the wheat crop in 2016, there was a significant effect of total rate of N on the production of yield-based N_2O (Table 2-1) with a positive linear trend [g N_2O-N emission per kg of grain = 0.0368+ 0.0005 x N rate (kg N ha^{-1}); p=0.004; R^2 =0.4]. An HSD test indicated that there were no significant effects of increasing the N fertilization rates ranging from 0 to 60 N ha^{-1}; however, when the fertilizer rates were 90 or 120 kg N ha^{-1}, we observed a significant increase in the N_2O produced on yield basis compared to the control.

Using a two-way ANOVA an effect of total N rate on yield-based N_2O production was detected, however, there was no significant difference between any of the pairs of equal N rate treatments in 2015 while in the 2016 growing season, both the total N rate and fertigation treatments significantly affected the yield-based N_2O emissions (Table 2-1). In 2016, at the 60 and 90 kg N ha^{-1} rates, we found significantly less yield-based N_2O produced in the fertigated treatment compared to the non fertigated treatment. Conversely, there was no difference between the fertigation and no fertigation treatment for fields receiving the highest N rate (120 kg N ha^{-1}) in our study.

2.4.1.3 N_2O Emission Factor

There was no significant effect of the two independent variables, total N rate or fertigation treatment, on emission factor in wheat in 2015, however, there was a significant effect of fertigation on the emission factor in wheat in 2016 (Table 2-1). Furthermore, comparisons between the two 60 kg N ha^{-1} treatments in 2016 showed that there were significantly higher emissions when fertigation was not used compared to the fertigation treatment; at 60 kg N ha^{-1} without fertigation the plots exhibited an EF 10 times larger than the equivalent 60 kg N ha^{-1} plots with fertigation. A similar result was seen at the 90 kg N ha^{-1} rate in 2016, there was a significantly 2.7-times higher EF when no fertigation was used to split the N fertilizer input. When 120 kg N ha^{-1} of fertilizer was applied, there was no significant difference in EF for the non fertigated and the fertigated treatments.

2.4.1.4 Soil Mineral Nitrogen

The most striking results of soil mineral N in wheat fields were the change in NO_3^- concentrations during the experimental year 2015 from basal values (10.9 and 11.7 mg N kg^{-1}) at pre-seeding in late April to much higher magnitudes ranging from 18 up to 114 mg N kg^{-1} in early June. Such a sharp increase can be attributed to the addition of granular side-banded urea at seeding as noticeable for several of the highest N rate treatments, 60 kg N ha^{-1} no fertigation, 120 kg N ha^{-1} no fertigation and 120 kg N ha^{-1} fertigation (Table 2-2). Later in the growing season, these NO_3^- concentrations were depleted and returned to near pre-seeding values. A similar trend for a NO_3^- spike was seen in May-June 2016, however the scale of the increase was not as large as in 2015. Regarding NH_4^+ concentrations during both growing seasons, relatively larger values were ascertained at pre-seeding 2015 (4.9 mg N kg^{-1} in 2015 and 3.0 mg N kg^{-1} in 2016) as well as shortly after the fertigation with UAN (Table 2-2).

2.4.2 Canola

2.4.2.1 Cumulative Area Based N_2O Fluxes

In 2015, N_2O production at N rates of 90 and 120 kg N ha^{-1} without fertigation (580.55 ± 436.59 and 345.03 ± 99.42 g N_2O-N ha^{-1} $year^{-1}$) were not significantly higher than the control (124.57 ± 34.76 g N_2O-N ha^{-1} $year^{-1}$). However, at a total rate of 60 kg N ha^{-1} without fertigation, the N_2O emissions (350.74 ± 54.08 g N_2O-N ha^{-1} day^{-1}) were significantly higher than the control although only marginally. In 2016, there was a significant effect of total N rate on N_2O production (Table 2-1). When 60 kg N ha^{-1} of fertilizer was added, the N_2O emissions were not significantly different from the control (56.08 ± 22.18 vs. 12.86 ± 8.55 g N_2O-N ha^{-1} $year^{-1}$) while increasing the total rate of N to 90 and 120 kg N ha^{-1} resulted in a significant increase in N_2O production above the control (130.47 ± 46.71 and 74.97 ± 22.30 g N_2O-N ha^{-1} $year^{-1}$, respectively). After an outlier was removed a linear model was fit to determine the relationship between N_2O emission and the rate of N fertilization in 2015 [N_2O emission (g N_2O-N ha^{-1}) = 165.33 + 1.94 x N rate; p=0.006; R^2 = 0.45] (Fig. 2-1b) and showed that there was a positive relationship between increasing N rate and N_2O production. A linear model was fit to determine the relationship between the N_2O emissions and the rate of N fertilization in 2016 [N_2O emission (g N_2O-N ha^{-1}) = 20.74 + 0.71 x N rate; p=0.007; R^2 = 0.41] (Fig. 2-1b) and was also found to be positive.

In 2015, an analysis of all treatments showed that there were no significant effects of the total rate of N or fertigation on N_2O emissions (Table 2-1). In 2016, there was a significant effect of the total rate of N on N_2O production and there was a significant effect of the total rate of N and its interaction with the fertigation treatment (Table 2-1). Comparisons showed that fertilization at equal rates produce the same amount of N_2O when fertigated and not fertigated.

2.4.2.2 Yield-based N_2O Emissions

An analysis of yield-based emissions in 2015 showed that there was a significant effect of total N rate on yield-based N_2O production (Table 2-1) with a positive linear trend [g N_2O-N emission per kg of grain = 0.0383 + 0.0154 x N rate (kg N ha^{-1}); p=0.18; R^2 =0.12]. When compared to the control, a fertilization rate of 120 kg N ha^{-1} did not produce significantly more yield-based N_2O. When 60 and 90 kg N ha^{-1} of fertilizer was used on the canola crop there were significantly higher yield-based N_2O emissions compared to the control. In 2016, the yield-based N_2O emissions for the canola crop were significantly affected by total N rate (Table 2-1) and had a positive linear trend [g N_2O-N emission per kg of grain =0.0084 + 0.0002 x N rate (kg N ha^{-1}); p=0.001; R^2 =0.33]. When N fertilization is increased from 0 to 60 or 120 kg N ha^{-1} there is no significant increase in the yield-based N_2O produced. When the rate of fertilizer was increased to 90 kg N ha^{-1}, there was a significant increase in the amount of yield-based N_2O produced compared to the control.

To compare fertigation with no fertigation yield-based emissions, the canola 2015 results show that there were no significant effects of the total N rate or the fertigation treatment while in 2016 there was a significant interaction between the total N rate and the fertigation treatment and a significant effect of total N rate (Table 2-1). Although there were significant effects in 2016, a comparison of the fertigated and non fertigated yield-based N_2O emissions at the 60, 90 or the 120 kg N ha^{-1} rates showed no significant differences.

2.4.2.3 N_2O Emission Factor

There was no effect of total N rate or fertigation on the EF in 2015 but there was a significant effect of the interaction between total N rate and fertigation treatment in 2016 (Table 2-1). However, it was found that when treatments of equal total N rate in 2016 were compared to each other, none of the pairs were significantly different.

2.4.2.4 Soil Mineral Nitrogen

Similar as for wheat, canola fields in 2015 exhibited moderate NO_3^- concentrations (8.2 and 8.3 mg kg^{-1}) at the pre-seeding sampling, which increased by one order of magnitude following the side banding of urea. The pattern of high NO_3^- in the early growing season was observed for the same treatments as in the wheat plots (60 kg N ha^{-1} no fertigation, 120 kg N ha^{-1} no fertigation and 120 kg N ha^{-1} fertigation) for which data is available (Table 2-2). Subsequently, following the soil NO_3^- peak, these concentrations decreased during the remainder of the 2015 growing season. Conversely, in 2016, granular side-banded urea at seeding caused a much lower increase in NO_3^- which was then gradually depleted over the growing season. With respect to NH_4^+ concentrations, treatments means were typically between 2 to 4 mg N kg^{-1} with the slightly larger values at pre-seeding in 2015 or shortly after the fertigation in 2016 (Table 2-2).

2.4.3 N_2O Comparisons across Experimental Years and Crop Species

There is a significant effect of the year ($p < 0.001$) and crop type ($p < 0.001$), as well as the interaction of year and crop type ($p < 0.01$) on N_2O emissions. The N_2O emission rate in the wheat crop in 2015 (522.73 ± 290.39 g N_2O-N ha^{-1} $year^{-1}$) was significantly higher than in 2016 (254.99 ± 136.47 g N_2O-N ha^{-1} $year^{-1}$) (Fig. 2-2). The same difference was observed in the canola crop. The canola N_2O emissions were significantly higher in 2015 (350.94 ± 243.25 g N_2O-N ha^{-1} $year^{-1}$) than in 2016 (70.63 ± 49.57 g N_2O-N ha^{-1} $year^{-1}$) (Fig. 2-2). The amount of N_2O emissions were also assessed by year by using the two-way ANOVA. Tukey post hoc tests show that in both 2015 and 2016, the wheat fields produced significantly more N_2O than the canola (Fig. 2-2).

2.4.4 Large N_2O Flux Events

Large flux events were identified visually from our graphic representations of the temporal patterns (Fig. 2-3 and 2-4) by observing the daily N_2O fluxes of each crop and each year and determining the flux sampling dates when the fluxes were higher than typical background. Five specific flux sampling dates were selected for conducting separate, further statistical examination (Table 2-3). Overall the largest pulse of N_2O in 2015 wheat fields was observed on 2 July 2015, in all treatments including the zero N control emitted between 13 to 32 g ha^{-1} day^{-1} without registering statistical differences in part because of the overwhelming spatial variability across experimental replicates (the coefficient of variation was 56% for this day). In the 2016 growing season, the largest daily fluxes in wheat were found on 26 May. The total N rate and fertigation treatments had both significant effects on the daily N_2O fluxes in wheat (Table 2-3). We found that when fertigation was not used at the 90 and 120 kg N ha^{-1} rates, the daily fluxes measured on 26 May were significantly higher than the unfertilized control (Fig. 2-5). Conversely, when fertigation was used, the only N rate that resulted in significantly higher N_2O emissions than the control was at the 120 kg N ha^{-1} rate (Fig. 2-5).

In our canola fields, we closely examined three peak N_2O flux events on 7 May 2015, 25 June 2015, and 26 May 2016 (Table 2-3). These three pulses from canola fields were comparatively lower than higher flux spikes from the wheat plots. Also, none of these three measurement dates resulted in statistical differences across any of the N treatments or control.

2.4.5 Weather and Irrigation

The total amount of natural precipitation at the research site between 1 April and 31 October in 2015 was 181 mm and another 196 mm was added using the irrigation system for a total water input of 377 mm (Fig. 2-6a). The amount of natural rainfall for these months was below the corresponding climate normals except in September. The total amount of natural precipitation at the site between 1 April and 31 October 2016 was 319 mm and another 127 mm was added using the irrigation system for a total water input of 446 mm (Fig. 2-6b). The amount of rainfall was higher than normal in May, July, August and October this year. The average amount of precipitation falling at the Lethbridge site between 1 April and 31 October (1971-2000 climate normals) is 301 mm (Government of Canada, 2017).

The average monthly temperatures during the 2015 and 2016 growing seasons were similar to the normal temperature values calculated for the area (Fig. 2-7). The summer months (i.e., June, July and August in 2015 and June in 2016) were slightly warmer than the normal.

2.5 Discussion

2.5.1 Nitrogen Rate Effects on Emission Factors

Although the sources and mechanisms involved in nitrous oxide production have been documented (Baggs, 2011; Butterbach-Bahl et al., 2013), emissions remain difficult to predict in field settings due to the interactions of multiple factors which drive and contribute to N_2O production. Nitrification and denitrification are controlled by soil conditions such as the concentration of mineral N, water content, temperature, texture, and organic matter (Butterbach-Bahl et al., 2013; Dobbie et al., 1999; Jamali et al., 2016) and the interaction between these factors as well as by management techniques such as irrigation timing and frequency, fertilizer management, cropping history and the presence and types of crops in both space and time (Bouwman, 1996). All of these factors lead to highly variable N_2O fluxes which can vary greatly within one field and from year to year.

The results of our field study show that increasing the N fertilizer rate applied at seeding in the wheat crop in both 2015 and 2016 resulted in a significantly positive relationship with N_2O emissions (Fig. 2-1). Although not all of the increases in N fertilizer rate resulted in a significant difference in N_2O emission above the control, the linear regression is still positive. These findings support the results from other studies which also show that increasing the application rate of N fertilizers leads to increased concentration of mineral N in the soil and thus an increase in N_2O fluxes (Bouwman, 1996; Dobbie et al., 1999; Grant et al., 2004; Mosier, 1994; Trost et al., 2013). Although, it is noteworthy that some studies did not show an increase in N_2O with increased N fertilizer rate (Zebarth et al., 2008). For the wheat crop, the N_2O emissions vs. total

N rate linear regressions showed very consistent slopes of 0.00244 kg N_2O-N kg^{-1} N fertilizer in 2015 and 0.00256 kg N_2O-N kg^{-1} N fertilizer in 2016. These coherent slope values can also be defined as the emission factor (EF) (Bouwman 1996) which is used to characterize N_2O emissions as a factor of applied N-fertilizer. However, these EF values in the wheat treatment are higher than values reported by Rochette et al. (2008) from Brown soils under rainfed conditions in the Canadian Prairies (0.001 kg N_2O-N kg^{-1} N fertilizer). The higher EF values from our experiment are likely attributed to the use of irrigation at this site and this was acknowledged by Rochette et al. (2008) who proposed a methodology for increasing the accuracy of estimating N_2O emissions on irrigated lands by adding a correction factor. According to our 2-yr field data, such an irrigation correction factor for EF under wheat cropping can be postulated as 2.5X. In agreement with the notion that the use of irrigation increases emissions, a review by Trost et al. (2013) found that in most cases N_2O emissions increased with irrigation under in a wide variety of soil types and climates; in further details, 6 of the 8 reviewed studies detected significant N_2O emissions increases when irrigation was implemented. The EFs calculated in our experiment confirm that in irrigated wheat fields, higher N_2O emissions should be expected compared to non-irrigated fields. It is assumed that irrigation increases the soil water content which increases biological activity and nutrient transformations and if excessive irrigation is applied it can decrease soil aeration which depletes oxygen in soil air and can lead to accelerated denitrification.

The N_2O fluxes measured from the canola crop also support a linear relationship between N_2O production and rate of fertilizer application in both 2015 and 2016. Not all N application rates resulted in significantly higher emissions from the control, but this is likely due to the high variability of in-field N_2O flux measurements. The EFs calculated for canola are 0.00194 kg N_2O-N kg^{-1} N in 2015 and 0.00071 kg N_2O-N kg^{-1} N in 2016. These values are similar to the estimated EF values summarized by Rochette et al. 2008 (0.001 kg N_2O-N kg N) for soils in the Canadian Prairies without irrigation. However, as discussed above, irrigation usually increases N_2O emissions. The lower EF values in the canola crop compared to the wheat could be attributed to the high nitrogen uptake and utilization of canola (Grant and Bailey, 1993; Stahl et al., 2016). A higher uptake of the applied N fertilizer can cause a reduction in the concentration of NH_4^+ and NO_3^- in the soil, thereby reducing the potential for nitrification and denitrification to produce N_2O as well as the total amount of fertilizer-N lost as N_2O (which is equivalent to EF). In other words, the added N fertilizer was apparently taken up rapidly by the canola crop before it could be used by N_2O-producing microbes via nitrification or denitrification. In our experiment, this direct relationship between yield and N rate was discernible in 2015; the wheat crop had a significant linear regression slope of 0.41 kg grain kg^{-1} N fertilizer, while the canola crop had a stronger positive relationship with a slope of 11.39 kg grain kg^{-1} N fertilizer (data not shown). Similar results have been found also by Kaiser et al. (1998) when comparing N_2O emissions between wheat and canola. As in our study (Fig. 2-2), they found that emissions from wheat plots are generally higher than those from canola. Future research can address the fate of N taken up by canola in the subsequent growing seasons as N_2O fluxes can respond to these putative legacy effects during canola residue decomposition.

2.5.2 Split N application via Fertigation Impacts on N_2O Emissions

When nitrogen fertilizers are applied early in the gowning season, plant uptake of N is low and is more vulnerable to transformation into N_2O gas (Grant et al., 2012). Split application of fertilizer has been found to reduce N_2O emissions in crops by controlling the supply of N available for nitrification and denitrification when plant use is low (Liu et al., 2011; Maharjan et al., 2014; Mosier, 1994) and allows for a synchrony between plant available N and plant uptake (Grant et al., 2012). In contrast, some studies have shown that in spring barley (Zebarth et al., 2008) and potato (Burton et al., 2008) split applications did not result in direct reduction of N_2O emissions. Our study shows varied results; there was no effect of split application via fertigation in 2015 in either crop or in 2016 for canola. When total N application rates were equal, the amount of N_2O measured was not significantly different when fertilizer was applied once, or when it was split using fertigation. However, in 2016 in the wheat crop, we found that using fertigation to split apply 90 kg N ha^{-1} resulted in significantly lower emissions of N_2O than when the same rate of fertilizer was applied once at seeding (Table 2-1). Upon close examination of the temporal patterns of the daily N_2O emissions, a clear difference in N_2O production between the fertigated and non-fertigated treatments at the 90 kg N ha^{-1} rate was recognized during a large flux event in the spring on 26 May (Fig. 2-4a), and this flux event was the major source of variation between the treatments on an annual basis. Fertigation did not occur until 7 June, therefore there were lower concentrations of mineral N in the soils of the fertigated treatments compared to their non-fertigated counterparts during these fluxes in late May. The 90 kg N ha^{-1} non-fertigated treatment, at this point in time, had the full amount (90 kg N ha^{-1}) of N fertilizer in the soil, but the fertigation treatments had 30 kg N ha^{-1} less. This higher amount of N in the non-fertigated treatments was not being utilized by the wheat crop early in the growing season and thus was vulnerable to nitrification and denitrification and associated N_2O losses. The 120 kg N ha^{-1} treatment from this year showed no significant differences between the fertigated and non fertigated treatment (Table 2-1). When the daily flux of the 120 kg N ha^{-1} treatment was examined, the N_2O production on 26 May was almost equal for fertigated and non-fertigated plots (Fig. 2-4a). This indicates that N additions at rates larger than 90 kg N ha^{-1} did not translate into additional increments in N_2O production. This could be explained because N substrate is not the only factor driving N_2O emission. Early in the growing season N_2O production could be limited by other soil factors such as soil organic carbon (Harrison-Kirk et al., 2013), aeration or texture (Jamali et al., 2016). From these results, we can determine that employing N management (fertigation) with total rates above 90 kg N ha^{-1} is ineffective to mitigate N_2O emissions because the early-season N_2O losses account for such a large portion of the cumulative fluxes and splitting N at these high rates (e.g., 90 kg N ha^{-1} at seeding and 30 kg N ha^{-1} at fertigation) does not reduce or delay enough N fertilizer to keep the critical May N_2O fluxes low. A threshold N rate of about 60 kg N ha^{-1} at seeding plus 30 kg N ha^{-1} at fertigation can be ascertained from our study with the aim of minimizing risk of N exposure leading to important N_2O losses.

2.5.3 Yield-scaled N_2O Emissions as a Productivity-Environmental Metric for Assessing N Management

N_2O emissions can also be described as yield-scaled emissions by comparing N_2O production per unit of grain yield (Maharjan et al., 2014). This approach attempts to make a connection between GHG emissions and crop productivity where low yield scaled emissions indicate a more efficient use of N fertilizer. Maharjan et al. (2014) found that the use of irrigation decreased yield scaled N_2O emissions and that adding fertilizer with the irrigation treatment (split application), decreased yield scaled N_2O emissions even more while Van Groenigen et al. (2010) determined that the best method to minimize yield scaled N_2O emissions was to maximize N uptake by crops and by applying fertilizer only up to plant uptake rates. In this experiment, we found that in both wheat and canola, increasing the fertilization rate above 0 kg N ha^{-1} generally increased the yield-based emissions (g N_2O-N emitted per kg of grain produced). Although not all comparisons were statistically different, linear regressions of yield-based N_2O emissions versus N rate show significantly positive trends.

When the fertigation treatment is compared to the non-fertigation treatment with an equal amount of applied N, significant differences in wheat were seen in 2016. Using fertigation to achieve applied N rates of 60 and 90 kg N ha^{-1} decreased yield scaled N_2O production compared to the treatments with no fertigation and the same total N application rate. Using fertigation as a method to split the application of N fertilizer not only results in lower emissions as seen in the previous section but it is also more efficient on a yield basis at 60 and 90 kg N ha^{-1} in wheat, but only in 2016. We can explain the discrepancy at these two rates in wheat by observing the differences in yield grain and N_2O emission. At the 60 kg N ha^{-1} rate, the average yield of wheat was similar between the fertigated (3861 kg dry matter grain ha^{-1}) and non-fertigated treatments (3974 kg dry matter grain ha^{-1}) but the associated N_2O emission for these plots was lower for the fertigated (114.82 g N_2O-N ha^{-1}) than the non-fertigated (249.38 g N_2O-N ha^{-1}) (Table 2-1). The same trend was seen in the 90 kg N ha^{-1} treatment from this year, yields were relatively similar (4207 kg dry matter grain ha^{-1} with fertigation and 4125 kg dry matter grain ha^{-1} without fertigation) while N_2O emissions were much higher when fertigation was not used (217.32 g N_2O-N ha^{-1} with fertigation and 411.23 g N_2O-N ha^{-1} without fertigation). These results demonstrate that when fertilizer rates are equal, the use of fertigation does not affect grain yields, however, it may reduce N_2O emissions depending on growing season conditions. When the total rate of N fertilizer was increased to 120 kg N ha^{-1}, the same trends were not observed - grain yields were still similar but the difference in N_2O emissions are not as great as those seen in the lower rates. This could be attributed to the large flux which occurred in late May, for the 120 kg N ha^{-1} treatments. At this rate, the fertigated plots had 90 kg N ha^{-1} applied in the spring while the non-fertigated had the full 120 kg N ha^{-1} applied at seeding. The early season high flux event, which made up a large amount of the cumulative flux, was similar between the two treatments (Fig. 2-4a). No differences were detected in the canola treatment in either year or in wheat in 2015 when treatments with equal total N were compared. Expressing N_2O emissions on a per yield basis may be more useful than reporting area-based N_2O emission because although reducing N rates will likely reduce N_2O emissions it may also decrease yields which in turn reduces the efficiency of the crop. Yield-based emissions provide a metric that informs environmental footprint intensity. Under critical scenarios where food production must be increased, trading off higher N_2O emission for proportionally higher yields could be acceptable.

2.5.4 Specific Soil-Weather Conditions leading to High Peak Fluxes

2.5.4.1 Peak Flux Dynamics and Drivers in 2015

Throughout the 2015 growing season the cumulative amount of N_2O produced can mostly be attributed to a few large flux events, otherwise fluxes remained close to zero (Fig. 2-3). In 2015 there were fluxes in May which were likely attributed to the application of urea into moist soil at the time of seeding and irrigation/ precipitation induced fluxes which were likely related to higher soil water content which occurred later in the growing season in July. In wheat, the amount of N_2O measured the day after granular side-banded fertilizer application (29 April) was between -0.2 and 0.4 g ha^{-1} day^{-1} and increased to 6.3 to 15.5 g ha^{-1} day^{-1} on 7 May. This early season N_2O flux, between seeding and fertigation (29 April to 8 June) made up a large proportion of the cumulative fluxes, ranging from 17 to 35% of the total growing season emissions. Treatments with 90 kg N ha^{-1} or more applied at seeding produced the highest fluxes. The small amount of rain before and during this flux event leads us to believe that the soil water was relatively low, and hence, unlikely to favor denitrification but would be relatively more conducive for nitrification-induced N_2O production (Linn and Doran, 1984). The application of fertilizer led to an abundance of mineral N in the soil following seeding, in particular NO_3^- (Table 2-2). This can indicate an increase in microbial activity and N transformations that led to high N_2O fluxes with even more production occurring at the highest rates. These interacting effects have been documented by Dobbie et al. (1999), Grant et al. (2004), Jamali et al. (2015), Mosier (1994) and Trost et al. (2013). Moreover, the snowfall between November and March before this spring flux, however, was below the 30-year average (Environment Canada, 2017) which further indicates the relatively dry soil conditions in the beginning of the growing season under the semi-arid climate of Southern Alberta. After some rainfall in mid-May (cumulative 12.7 mm in five days), a second pulse in N_2O production can be seen in the wheat crop in 2015 (Fig. 2-3a).

Similar to wheat, in 2015, the canola plots had very little N_2O production the day after granular side-banded fertilizer application (0 to 1.1 g ha^{-1} day^{-1}), but fluxes quickly increased to a peak of 3.8 to 10.1 g ha^{-1} day^{-1} within the following weeks (Fig. 2-3b). These early season N_2O emissions made up a large proportion of the cumulative N_2O fluxes this year, the emissions between seeding and fertigation (between 29 April and 8 June) ranged from 20% in the control to

65% for the 120 kg N ha^{-1} without fertigation. This continuous flux event can support the notion that this May emission is attributed more to nitrification than to denitrification. The rain fall occurring in mid-May 2015 only caused an increase in N_2O flux in the plots with the highest initial N rate (120 kg N ha^{-1} applied at seeding). The soil nitrogen measurements also revealed that there were very high NO_3^- concentrations in the soil in early June, several weeks after the application of granular side-banded urea in 2015. The presence of high NO_3^- concentrations is likely associated also with soil N transformations such as nitrification coupled with low plant uptake which might have caused in part the high May fluxes (Table 2-2). The results from both the canola and wheat plots indicate that the effect of increased soil water content was only effective at increasing N_2O production when mineral N concentrations in the soil were high following additions of high N fertilizer rates.

The second major event contributing significantly to the cumulative N_2O flux in 2015 in both wheat and canola occurred in mid-June to early-July after a large irrigation event (Fig. 2-3c). Earlier studies have documented how increased soil wetness stimulates N_2O emissions the production of N_2O in irrigated orchards (Fentabil et al., 2016a; Fentabil et al., 2016b), annual row crops (Dobbie et al., 1999; Liu et al., 2011; Ruser et al., 2006) and pastures (Dobbie et al., 1999; Rudaz et al., 1989). These studies attribute the increased soil water either from irrigation, induced wetting in a lab or natural precipitation as the reason for higher N_2O fluxes. In our study, after a large irrigation event on 16 June 2015 of 37 mm, the daily flux of N_2O increased in both crops and all N treatments (Fig. 2-3a and b). Additional irrigation and rain occurrences on 22 and 23 June (12 and 35.5 mm, respectively) probably lead to excessive and prolonged high soil moisture, and likely increased the amount of denitrification N_2O being produced. Although there were no significant effects of fertigation or N rate on emissions on this date, a clear trend of higher emissions produced by the higher rates of N was observed and can be explained by the higher levels of NH_4^+ and NO_3^- present in the soil during this large flux (Table 2-2). In contrast to the early season fluxes, the fertigated treatments generally had higher emissions of N_2O than their equal N rate counterparts without fertigation. This is likely due to the recent application of the additional 30 kg N ha^{-1} of UAN in the fertigation treatments which readily became N substrate available to microbes for denitrification upon the rapid increase in soil moisture. The same trend is observed in the canola plots although the magnitude of the flux is not as great as in the wheat. There was no statistical significance found but the largest fluxes, again, are seen in those treatments that had just received additional fertilizer through fertigation.

2.5.4.2 Peak Flux Dynamics and Drivers in 2016

Spring fluxes in late May after fertilizer application were also seen in 2016 in both crops (Fig. 2-4). As discussed above, this spring flux was primarily responsible for the differences seen in the fertigated and non fertigated treatments in wheat at median N rates. Seeding of the crop and granular urea application occurred on 5 May which increased mineral N concentrations and led to a gradual increase in N_2O emissions in wheat after this date (Table 2-2) (Fig. 2-4a). Daily N_2O emissions in wheat increased from 0.3 to 1.5 g ha^{-1} day^{-1} in early May to 2.4 to 6.9 g ha^{-1} day^{-1} on 26 May. Three of the treatments were significantly different from the control on this day: 90 kg N ha^{-1} without fertigation, 120 kg N ha^{-1} without fertigation and 120 kg N ha^{-1} with fertigation (Table 2-3). We can observe that applying over 90 kg N ha^{-1} of fertilizer at seeding creates a risk of high N_2O loss since the recently-added nutrient is not required or utilized by plants at this early growth stage (Jamali et al., 2016; Liu et al., 2011; Maharjan et al., 2014).

Splitting the application of high rates of N can be useful to reduce early season N_2O while likely increasing nutrient-use efficiency by crops. The major fluxes in spring 2016 between 13 May and 2 June occurred following six consecutive days of rainfall beginning on 19 May that amounted to a total of 38.9 mm of water (Fig. 2-4c). These rainfall events can contribute enough water to increase soil moisture to a level at which microbial activity and N transformations as well as denitrification can be favored. These rainfalls occurred slowly throughout multiple days and gradually wetted the soil and kept it moist leading to the episode of peak fluxes in May. Moreover, plant uptake during this time was also likely low due to early growth stages, thus also less water was being removed by these crops further contributing to prevalent field moist conditions.

Daily N_2O emissions in the spring in canola increased from 0.3 to 0.65 g ha^{-1} day^{-1} to 0.5 to 5.3 g ha^{-1} day^{-1}, also likely as a result of the rainfall event starting on 19 May causing denitrification. There were no significant differences in any of the treatments compared to the control but the plots with higher rates of N added at seeding had the highest spring fluxes similar to what was seen in wheat in 2016.

The irrigation induced N_2O emissions in 2016 differ from those seen in this study in 2015; there was no effect of increased irrigation on N_2O production in 2016. A large irrigation event of 51 mm occurred on 4 July; however, this irrigation did not cause a spike in N_2O production as the one seen in the previous year for either wheat or canola. This may be attributed to the large plant canopy at this time which could have a high-water uptake ability thereby reducing the soil moisture and decreasing the amount of denitrification induced N_2O production. The absence of a spike in N_2O emissions after this large irrigation event may also be attributed to the extended lag in time before the next water input took place: 8.5 mm of rain on 11 July, followed by 13 mm on 12 July and 27.5 mm on 13 July; this seven-day time lag may have been long enough for soil moisture to decrease below a level optimal for denitrification. It should be noted that the maximum temperature the week following this large irrigation event was uncommonly high which may have increased evapotranspiration flux leading to lower soil water contents. However, the effects of high temperature could also be counteracting because higher temperatures can also increase microbial activity and N_2O losses (Butterbach-Bahl et al., 2013; Dobbie et al., 1999; Hernandez-Ramirez et al., 2009).

Spring fluxes of N_2O in late May were evident in both years and are likely attributed to a combination of nitrification and denitrification processes as function of field moisture conditions. As noted above, fluxes increased when N fertilization rates were increased, supporting the assumption that splitting and delaying fertilizer addition to match the timing of active plant uptake could lead to lower N_2O emissions in the early growing season. Later season fluxes seem to be moisture-induced in 2015 and occurred immediately after major irrigation events and were likely due to high soil moisture and associated denitrification, but this response was not seen in 2016 even after an even heavier irrigation event. Despite the use of irrigation, the dry climate and high evapotranspiration at the study site may have resulted in the soil wetness to be moderate or even low which may have suppressed the N_2O emissions from both crops when compared to much wetter environments. The total amount of water input in 2015 was 452 mm, and in 2016 was 475 mm, this included irrigation and rainfall which is close to the annual potential evapotranspiration (PET) in Lethbridge for canola (359 to 467 mm) and lower than the annual PET for wheat (419 to 538 mm). Given these likely water-limiting conditions, it may be that denitrification-induced pulses of N_2O production occur only sporadically as a major source in southern Alberta; conversely, intense nitrification-caused by high N urea addition rates at seeding can still be an important source of steadier N_2O emissions in these annual cropping systems.

2.5.5 Interannual Variations of N_2O Emissions

A comparison of the fluxes during the two study years shows that there were significantly higher N_2O emissions in 2015 than 2016 in both wheat and canola crops (Fig. 2-2). Both experimental years showed peak emissions in May, but only 2015 exhibited important pulse emissions in the period of late June-early July. Emissions in wheat fields were doubled in 2015 compared to 2016, and canola was seven times higher in 2015. This interannual variation can be explained by differences in soil nitrogen levels (Table 2-2). Soil nitrate concentration in both the wheat and the canola crops increased greatly following the application of granular side-banded urea at seeding in 2015; the scale of this nutrient availability increase was much greater than the one seen in 2016. Irrespective of the crop species, such increases in NO_3^- concentration during the early growing seasons were 6-fold and up to 9-fold in 2015 whereas in 2016 this NO_3^- increase was only 2-fold change. As previously mentioned, the rates of nitrification and perhaps mineralization early in 2015 seem to be high, causing not only an increased flux of N_2O but also the production and accumulation of NO_3^-. These higher NO_3^- concentrations were concurrent with higher cumulative fluxes in 2015 than in 2016. Overall, these results highlight the driving role of N substrate availability on N_2O fluxes (as further described in Chapter 3). More data on annual cumulative emissions would be useful for determining the variability in fluxes in relationship with N availability.

It is plausible that N_2O flux differences between years can also be attributed to the differences in frequency and intensity of wetting and drying cycles as induced by the implementation of irrigation. Beare et al. (2009), Borken and Matzner (2009), and Ruser et al. (2006) found that microbial activity increases when soil is recurrently rewetted after being dried; the rewetting of a dry soil increases the availability of organic matter in the soil pores by making available organic matter that was previously unavailable to the microbes which causes an increase in soil nutrient availability, creates a pulse in carbon from dead microbes which died during drying, and causes the release of substrates into soil system. Borken and Matzner (2009) also point out that cumulative N mineralization can be increased by increasing the wetting intensity (through higher volumes of water) and decreasing the duration of the drying period. In our experiment, irrigation reduced the length of time between these cycles of water input compared to conventional rainfed fields; therefore, decreasing drying periods and increasing N mineralization. High rates of irrigation may have induced pulses of mineralization which would not have occurred with normal rain. It is likely that the application of irrigation reduced the strength of the wetting and drying cycles making moist conditions more predominant and constant within the soil and also increased the overall wetness intensity which would have led to higher fluxes of N_2O than if irrigation was not used (Jambert et al., 1997; Liu et al., 2011; Trost et al., 2014).

2.6 Conclusion

Increasing the total rate of applied N fertilizer to both wheat and canola showed consistently positive feedback towards larger N_2O emissions. The EFs calculated for our irrigated wheat fields were much higher than the previously reported EFs for rainfed wheat in comparable regions and are likely attributed to the use of irrigation leading to soil wetness and favorable conditions for nutrient transformations. The EFs calculated for canola were lower than our EFs for wheat and are likely attributed to the higher N uptake capacity of canola directly reducing the exposure risk and susceptibility of available soil N to be transformed and lost as N_2O to the atmosphere.

It was found that using fertigation to split-apply nitrogen fertilizers in canola did not lower the area- or yield-based N_2O emissions in both experimental years (2015 and 2016). A similar result was observed for wheat in 2015; however, in 2016 there was a significant reduction in area based N_2O emissions at 90 kg N ha^{-1}, and in yield-based N_2O emission at 60 and 90 kg N ha^{-1} in wheat fields receiving fertigation. During the two assessed growing seasons, the major source of the flux variation was observed in the large pulses of N_2O in May. Furthermore, in late May 2016, these peak emissions generated more N_2O from fields where all the N fertilizer had been added at seeding, and hence, had higher N input prior to the time of the flux events. The higher risk for N_2O losses appears to be within four weeks after N addition at seeding. The timing of the major N_2O fluxes relative to application of urea, along with the field wet conditions, could suggest that denitrification contributed to the N_2O emissions in these fields. Therefore, reducing mineral N concentration in the soil through split N fertilization may be an appropriate management technique to lower N_2O emissions. Other peak fluxes later in the growing season (early July 2015) were attributed to large irrigation events; however, these mid-season emissions were inconsistent across the two study years.

2.7 Acknowledgments

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2.9 Tables

Table 2-1. Effects of total N rate on annual cumulative N_2O emissions, yield-based N_2O emissions and emission factor with grain yield data, and the effect of total N rate and fertigation on annual cumulative N_2O emissions, yield-based N_2O emissions and emission factor with grain yield data in 2015 and 2016 for wheat and canola.

	Area based N_2O emissions ($g\ N_2O\text{-}N\ ha^{-1}$)^z				**Grain dry matter ($kg\ ha^{-1}$)**				**Yield-based N_2O emissions ($g\ N\ kg\ grain^{-1}$) ^{z}**				**Emission Factor ^{z}**			
Crop	Wheat		Canola		Wheat		Canola		Wheat		Canola		Wheat		Canola	
Year	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Treatment																
0 kg N ha^{-1}	375.0 a	101.0 a	124.6 a	12.9 a	6395.3	2894.0	3660.0	2278.3	0.056 a	0.034 a	0.034 a	0.006 a	-	-	-	-
60 kg N ha^{-1}	469.4 a	249.4 ab	350.7 b	56.1 ab	6817.8	3973.8	4393.5	3215.0	0.069 a	0.063 ab	0.080 b	0.017 a	1.872 a	2.472 a	3.769 a	0.720 ab
90 kg N ha^{-1}	524.3 a	411.2 b	580.6 a	130.5 c	6707.5	4125.3	4757.0	3470.8	0.078 a	0.100 b	0.121 b	0.038 b	1.858 a	3.447 a	5.066 a	1.307 a
120 kg N ha^{-1}	668.1 a	374.0 b	345.0 a	75.0 b	6721.5	4430.8	4763.8	3807.0	0.099 a	0.084 b	0.072 ab	0.020 a	2.592 a	2.275 a	1.837 a	0.5176 b
p-value ^{y}																
Total N rate	N.S	**	**	***	-	-	-	-	N.S	**	*	***	N.S	N.S	N.S	*
Statistical test	One-way ANOVA	One-way ANOVA	Welch's ANOVA	One-way ANOVA	-	-	-	-	One-way ANOVA	One-way ANOVA	One-way ANOVA	One-way ANOVA	One-way ANOVA	One-way ANOVA	One-way ANOVA	One-way ANOVA
Data transformation	None	None	None	None	-	-	-	-	None	Box cox	Box Cox	None	None	Box Cox	Box Cox	None
Treatment																
60 kg N ha^{-1} No Fertigation	469.4 a	249.4 a	350.7 a	56.1 a	6817.8	3973.8	4393.5	3215.0	0.069 a	0.063 a	0.080 a	0.017 a	1.87 a	2.47 b	3.77 a	0.72 a
60 kg N ha^{-1} Fertigation	446.8 a	114.8 a	360.8 a	33.3 a	6524.5	3860.8	4632.8	3100.3	0.068 a	0.030 b	0.078 a	0.011 a	1.50 a	0.23 a	3.94 a	0.34 a
90 kg N ha^{-1} No Fertigation	524.3 a	411.2 a	580.6 a	130.5 b	6707.5	4125.3	4757.0	3470.8	0.078 a	0.100 a	0.121 a	0.038 a	1.90 a	3.45 b	5.07 a	1.31 a
90 kg N ha^{-1} Fertigation	323.7 a	217.3 b	343.7 a	70.6 b	6478.0	4207.0	4322.3	3389.8	0.050 a	0.052 b	0.079 a	0.021 a	-0.37 a	1.29 a	2.43 a	0.64 a
120 kg N ha^{-1} No Fertigation	668.1a	374.0 a	345.0 a	75.0 b	6721.5	4430.8	4763.8	3807.0	0.100 a	0.084 a	0.072 a	0.020 a	2.59 a	2.28 a	1.84 a	0.52 a
120 kg N ha^{-1} Fertigation	869.9 a	317.1 a	351.2 a	116.1 b	6201.5	4455.3	4816.3	3857.3	0.140 a	0.071 a	0.073 a	0.029 a	4.27 a	1.80 a	1.89 a	0.86 a
p-value ^{y}																
Total N rate (N)	*	**	N.S	*	-	-	-	-	*	**	N.S	*	N.S	N.S	N.S	N.S
Fertigation (F)	N.S	**	N.S	N.S	-	-	-	-	N.S	***	N.S	N.S	N.S	***	N.S	N.S
Interaction (N x F)	N.S	N.S	N.S	*	-	-	-	-	N.S	N.S	N.S	*	N.S	N.S	N.S	*
Statistical test	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	-	-	-	-	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA

Data transformation	Box Cox	None	Box Cox	None	-	-	-	-	Box Cox	Box Cox	Box Cox	None	Box Cox	None	Box Cox	None

[Z] Effects were tested by comparing the treatments against the control within each year and crop for the one-way ANOVA analysis and only tested within treatments with the same total N rate over each year and crop for the two-way ANOVA analysis. Same letters indicate no significant differences based on Tukey HSD.

[Y] *, **, *** and N.S indicate a significant treatment effect based on ANOVAs at $p \leq 0.05$, 0.01, 0.001, or no significant effect, respectively.

Table 2-2. Measured soil NH4+ and NO3- concentration in wheat and canola fields at the 0-15 cm soil depth increment at various times during the growing seasons in 2015 and 2016 in mg N kg^{-1} soil.

	2015				**2016**				
Treatment	**Pre-seeding (14 April)**	**4 days prior to fertigation (4 June)**	**10 days after fertigation (18 June)**	**After harvest (28 August)**	**Pre-seeding (19 April)**	**After seeding (15 May)**	**4 days prior to fertigation (3 June)**	**10 days after fertigation (17 June)**	**After harvest (31 August)**
					NH_4^+ Wheat				
0 kg N ha^{-1}	4.71	3.55	4.83	3.32	2.98	2.68	2.28	2.66	2.30
60 kg N ha^{-1} No Fertigation	4.71	3.83	4.05	3.32	2.98	2.40	2.62	2.12	2.45
60 kg N ha^{-1} Fertigation	4.90	3.73	4.33	2.98	2.46	3.41	2.34	2.09	2.81
90 kg N ha^{-1} No Fertigation	4.71	-	-	3.32	2.98	-	-	-	2.44
90 kg N ha^{-1} Fertigation	4.90	-	-	2.98	2.46	-	-	-	2.70
120 kg N ha^{-1} No Fertigation	4.71	3.86	5.13	3.32	2.98	2.81	3.05	2.30	2.90
120 kg N ha^{-1} Fertigation	4.90	3.89	5.79	2.98	2.46	4.56	2.42	2.54	2.64
					NO_3^- Wheat				
0 kg N ha^{-1}	11.68	15.94	11.83	12.12	10.32	5.16	5.09	2.85	5.88
60 kg N ha^{-1} No Fertigation	11.68	53.81	14.82	12.12	10.32	16.76	12.01	8.40	5.97
60 kg N ha^{-1} Fertigation	10.88	18.62	16.99	14.56	8.27	15.19	5.71	8.99	5.83
90 kg N ha^{-1} No Fertigation	11.68	-	-	12.12	10.32	-	-	-	4.67
90 kg N ha^{-1} Fertigation	10.88	-	-	14.56	8.27	-	-	-	6.12
120 kg N ha^{-1} No Fertigation	11.68	113.54	22.29	12.12	10.32	25.44	13.50	15.19	7.28
120 kg N ha^{-1} Fertigation	10.88	58.61	34.23	14.56	8.27	19.53	11.75	15.66	5.37
					NH_4^+ Canola				
0 kg N ha^{-1}	3.89	3.34	4.66	2.96	2.13	3.66	2.26	1.96	2.30
60 kg N ha^{-1} No Fertigation	3.89	3.51	3.67	2.96	2.13	2.86	2.26	2.12	2.45
60 kg N ha^{-1} Fertigation	3.83	2.98	4.18	2.90	2.68	2.68	3.77	2.43	2.81
90 kg N ha^{-1} No Fertigation	3.89	-	-	2.96	2.13	-	-	-	2.44

90 kg N ha^{-1} Fertigation	3.83	-	-	2.90	2.68	-	-	-	2.70
120 kg N ha^{-1} No Fertigation	3.89	3.55	3.78	2.96	2.13	2.95	3.80	2.41	2.90
120 kg N ha^{-1} Fertigation	3.83	3.17	3.89	2.90	2.68	2.86	3.52	2.48	2.64
NO_3^- Canola									
0 kg N ha^{-1}	8.22	21.79	13.83	13.00	8.05	13.04	6.26	3.21	5.88
60 kg N ha^{-1} No Fertigation	8.22	54.28	15.00	13.00	8.05	17.75	12.11	7.39	5.97
60 kg N ha^{-1} Fertigation	8.29	21.85	21.52	15.64	10.96	13.69	10.35	11.08	5.83
90 kg N ha^{-1} No Fertigation	8.22	-	-	13.00	8.05	-	-	-	4.67
90 kg N ha^{-1} Fertigation	8.29	-	-	15.64	10.96	-	-	-	6.12
120 kg N ha^{-1} No Fertigation	8.22	64.62	19.88	13.00	8.05	12.05	22.10	11.06	7.28
120 kg N ha^{-1} Fertigation	8.29	97.88	34.24	15.64	10.96	7.76	19.98	18.07	5.37

Table 2-3. Effects of total N rate and fertigation on daily N_2O flux on major flux days in wheat and canola in 2015 and 2016.

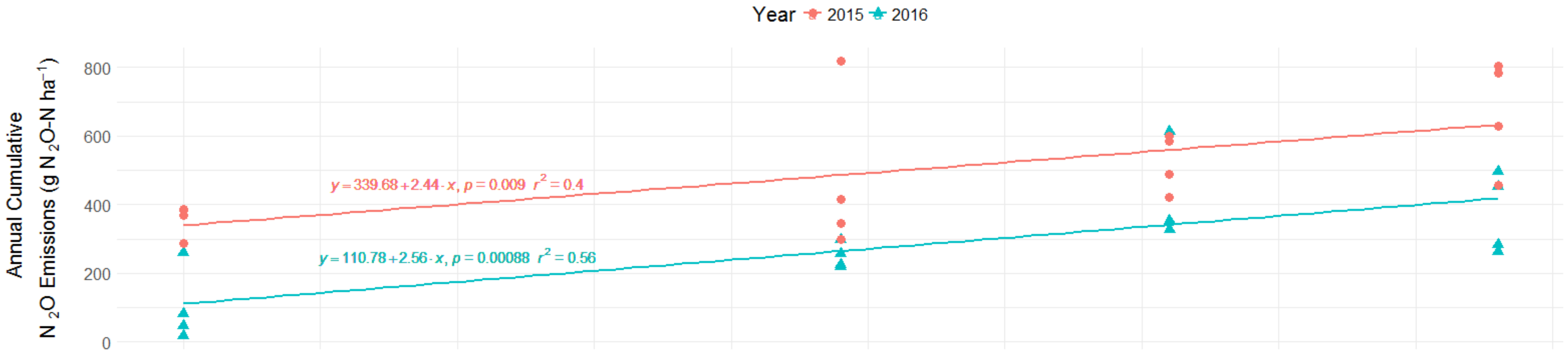
	Daily N_2O emission (g ha^{-1} day^{-1})^z				
Crop	**Wheat**		**Canola**		
Date	**2 July 2015**	**26 May 2016**	**7 May 2015**	**25 June 2015**	**26 May 2016**
Treatment					
0 kg N ha^1 No Fertigation	13.01 a	2.30 a	2.36 a	2.43 a	2.16 a
60 kg N ha^{-1} No Fertigation	16.52 a	8.88 abc	10.56 a	4.12 a	5.49 a
60 kg N ha^{-1} Fertigation	25.12 a	1.31 a	6.01 a	3.68 a	2.52 a
90 kg N ha^{-1} No Fertigation	17.02 a	14.53 bc	11.14 a	5.43 a	7.22 a
90 kg N ha^{-1} Fertigation	21.36 a	7.70 ab	9.70 a	6.91 a	4.10 a
120 kg N ha^{-1} No Fertigation	32.01 a	18.96 c	9.51 a	3.26 a	6.30 a
120 kg N ha^{-1} Fertigation	28.24 a	16.10 bc	9.06 a	4.89 a	7.35 a
p-value^y					
Total N rate	N.S	***	N.S	N.S	N.S
Fertigation	N.S	**	N.S	N.S	N.S
Interaction	N.S	N.S	N.S	N.S	N.S
Statistical test	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA	Two-way ANOVA
Data transformation	None	None	Box Cox	Box Cox	Box Cox

^{Z} Same letters indicate no significant differences based on Tukey's HSD.

^{Y} *, **, *** and N.S indicate a significant treatment effect at p≤ 0.05, 0.01, 0.001, or no significant effect, respectively.

2.10 Figures

a) Wheat



b) Canola

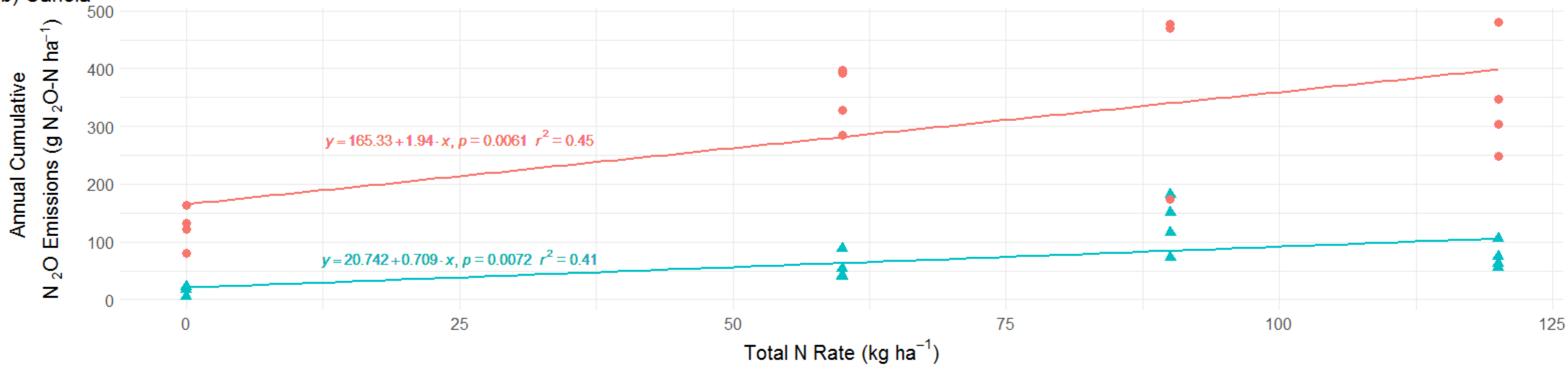


Figure 2-1. Annual cumulative N_2O emissions of wheat at different total N fertilization rates without fertigation application in 2015 and 2016.

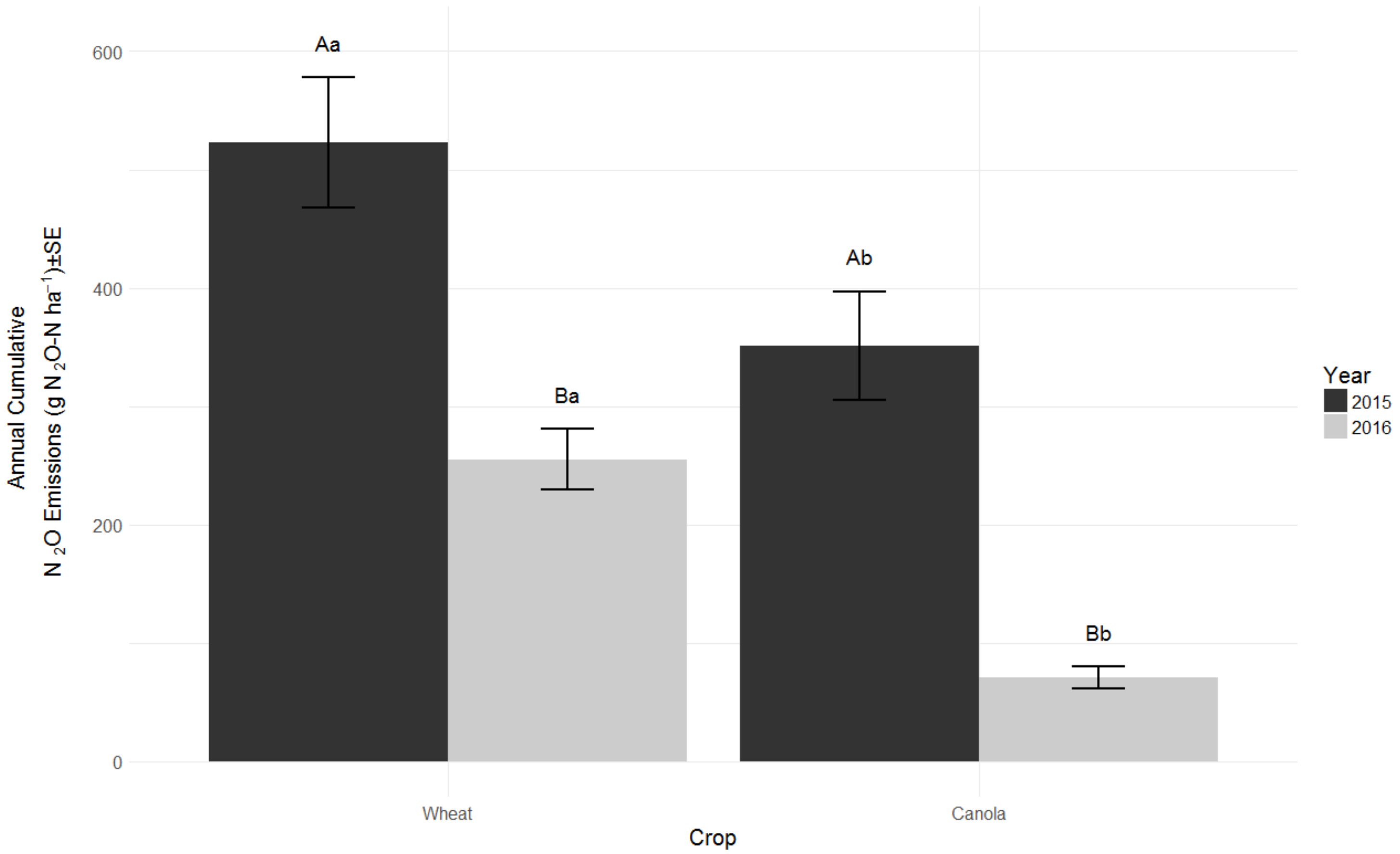


Figure 2-2. Annual cumulative emissions of N_2O in canola and wheat in 2015 and 2016. Includes all experimental treatments. Upper case letters represent comparisons between years of the same crop. Lower case letters represent comparisons between crops in the same year.

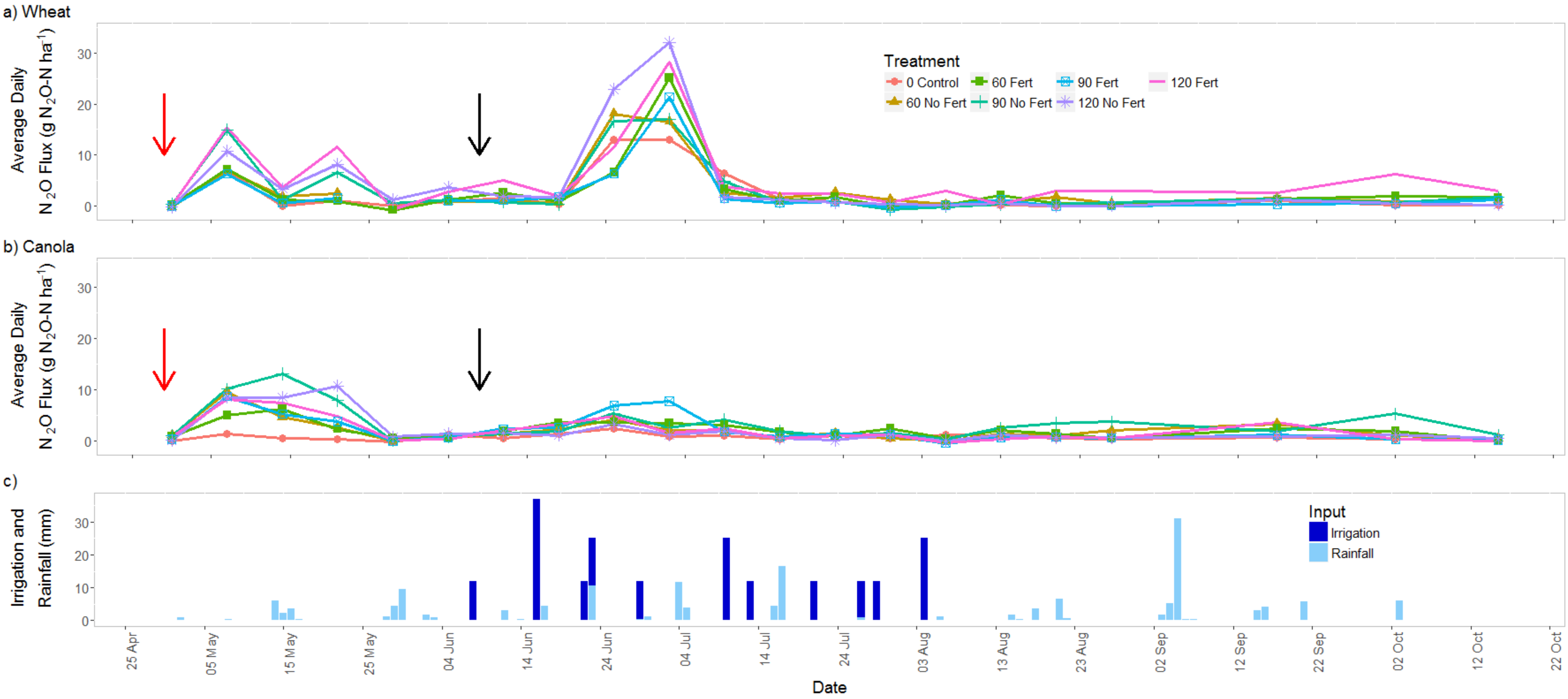


Figure 2-3. Average daily N_2O flux of all treatments in a) wheat and b) canola with c) the total amount of precipitation and irrigation in 2015. Red arrows indicate the date of seeding and granular urea application, black arrows indicate the date of fertigation.

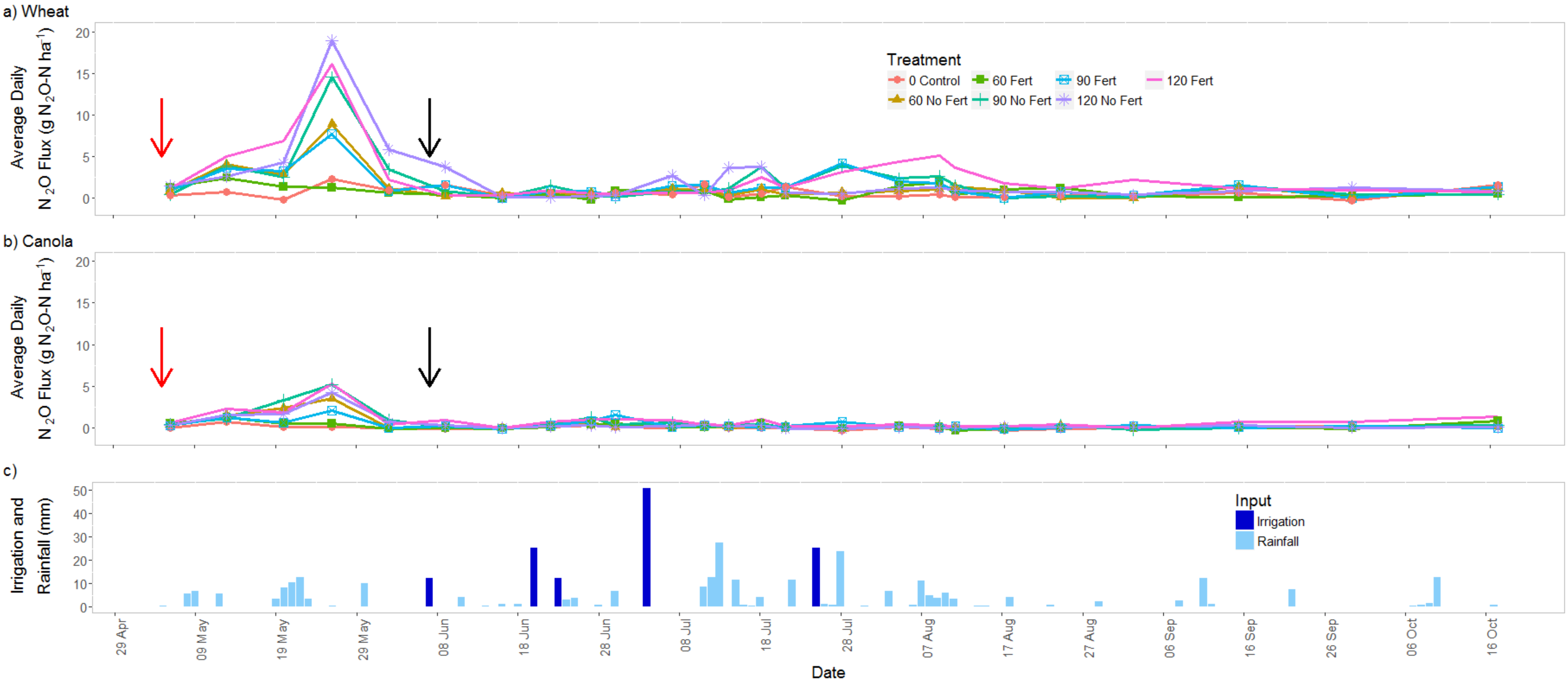


Figure 2-4. Average daily N_2O flux of all treatments in a) wheat and b) canola with c) the total amount of precipitation and irrigation in 2016. Red arrows indicate the date of seeding and granular urea application, black arrows indicate the date of fertigation.

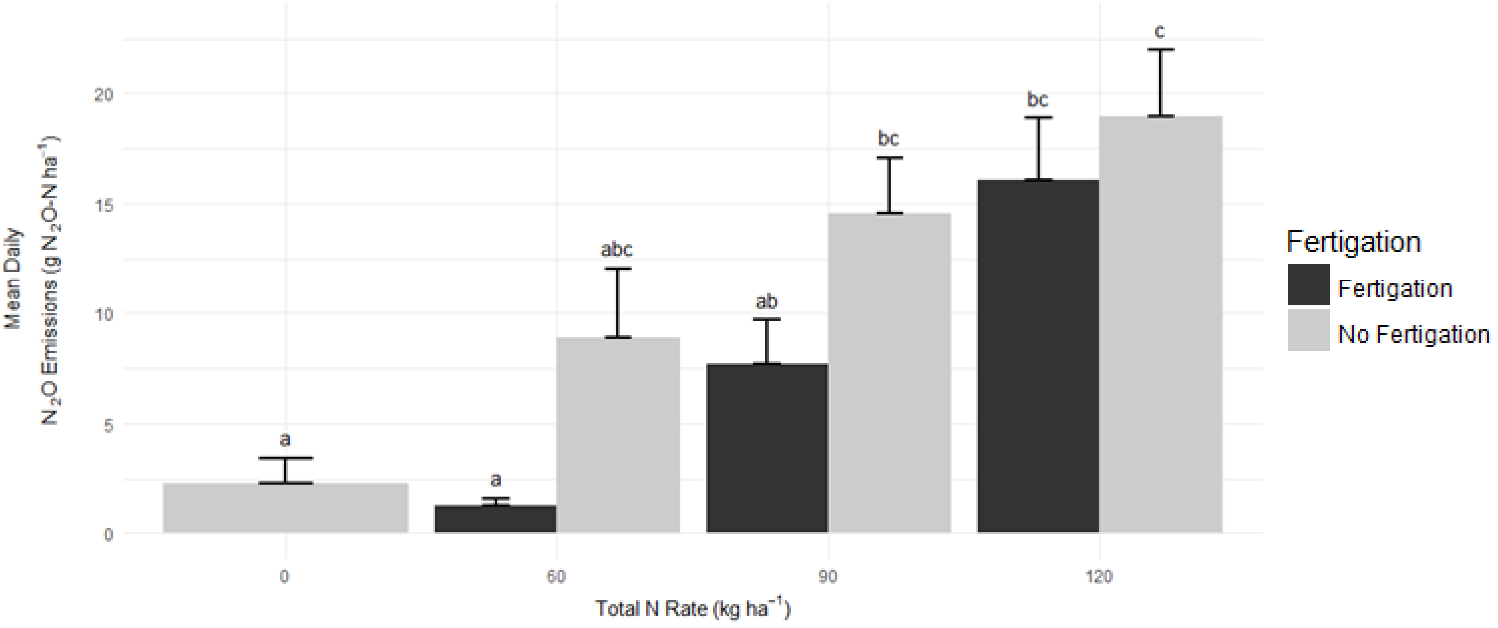


Figure 2-5. Mean daily N_2O emissions in the wheat treatment on May 26, 2016 for each of the treatment combinations of total N rate and fertigation.

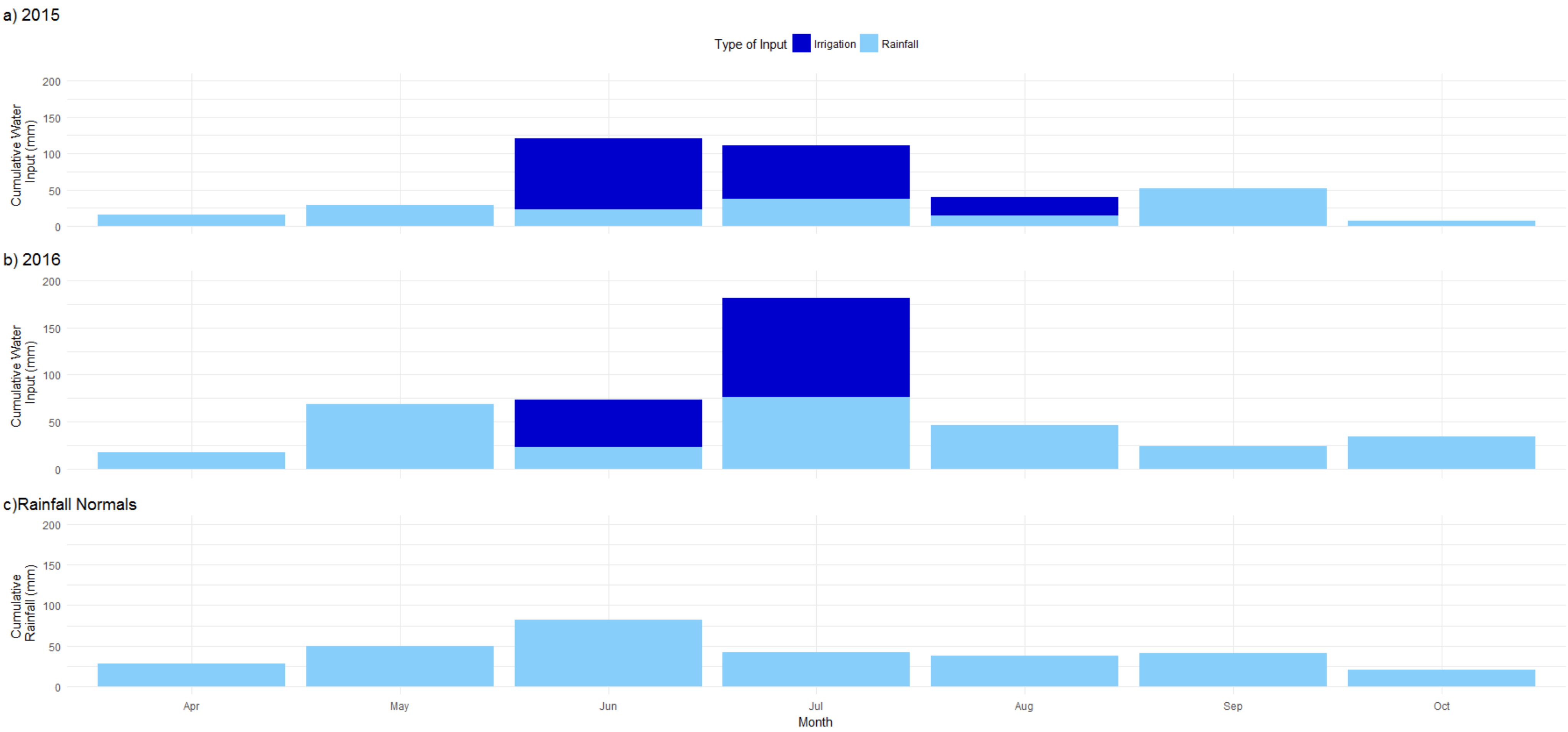


Figure 2-6. Growing season water input in the forms of precipitation and irrigation in a) 2015 and b) 2016 and c) precipitation normal (1971-2000) in Lethbridge, Alberta.

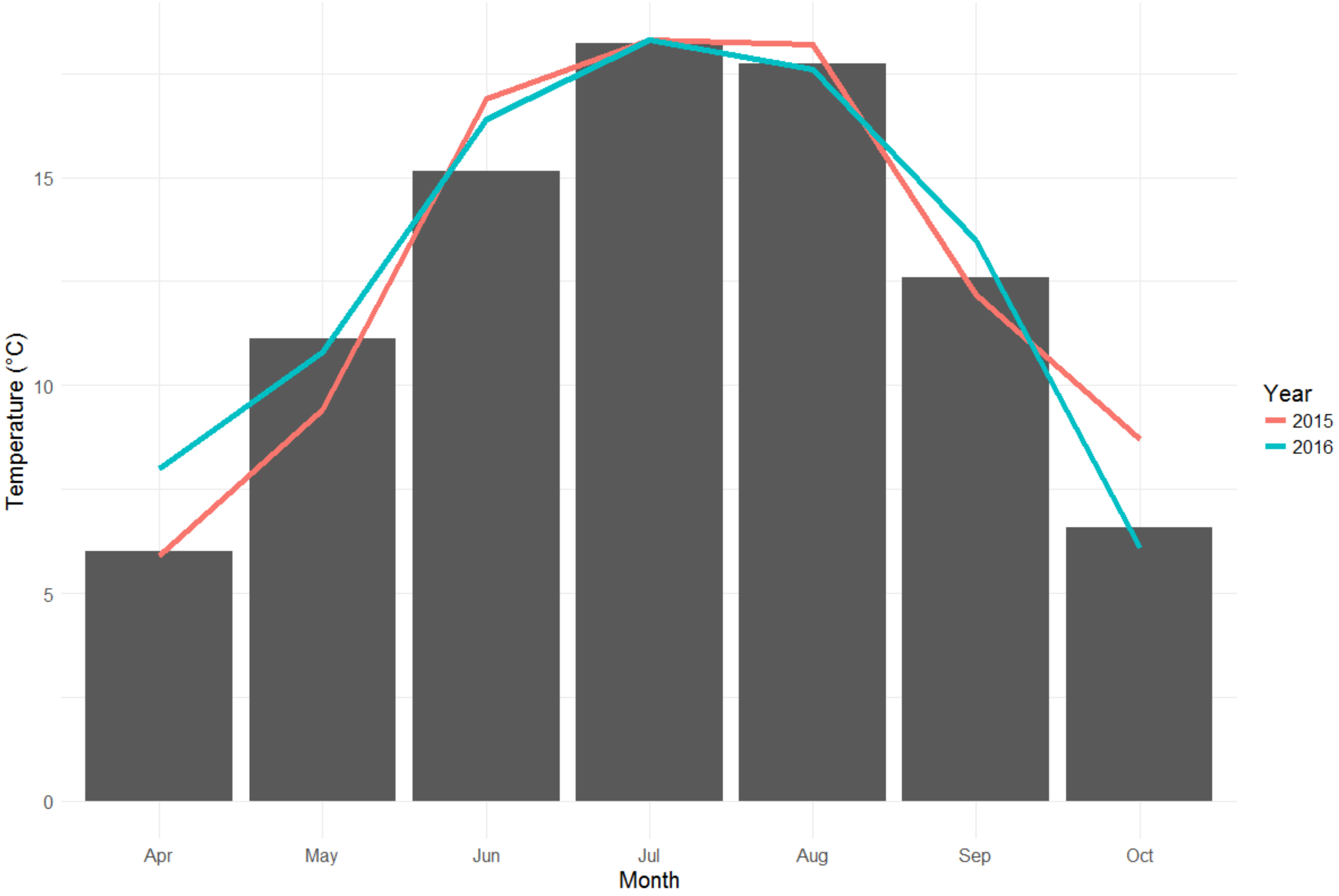


Figure 2-7. Average monthly air temperature in Lethbridge, Alberta. Bars indicate temperature normal for Lethbridge, Alberta (1971-2000).

3. Soil Nitrous Oxide Production as influenced by Nitrogen and Moisture Regimes: Effects of Recent In-Crop Fertigation and Nitrate Availability

3.1 Abstract

Nitrous oxide (N_2O) production in agricultural soils can be affected by management practices such as irrigation and nitrogen fertilization. The practice of applying fertilizer along with irrigation water (fertigation) is a technique that can facilitate splitting the crop N fertilizer requirement into smaller doses to better synchronize available N in the soil with crop N demand, and reduce the amount of N_2O produced. However, the frequent application of irrigation water keeps soil moisture content in a range (near field capacity) that may facilitate N_2O emissions. The objective of this study was to evaluate the response of soil N_2O emissions to the splitting of N fertilizer using fertigation at different rates and at different moisture regimes from soils collected from irrigated wheat fields. For this laboratory incubation, we sampled soils from a field experiment located in Southern Alberta in mid June 2016. The field treatments were total N fertilizer rates of 0, 90 or 120 kg N ha^{-1} using conventional fertilization (i.e., granular, side-banded urea applied at crop seeding) or split N application using fertigation (i.e., fertilizer applied at two timings: urea applied at seeding at 60 or 90 kg N ha^{-1} plus 30 kg N ha^{-1} of UAN through fertigation done at wheat tillering in early June). The soils were incubated for 32 days at three moisture regimes to simulate a typical range of irrigated conditions: a control kept at a constant 60% water filled pore space (WFPS), a weak drying regime fluctuating from 64 to 56% WFPS and a moderate drying treatment from 64 to 50% WFPS. The N_2O flux sampling (ten times during the incubation period) revealed that the use of fertigation to split the 90 kg N ha^{-1} rate produced significantly more N_2O than when all the 90 kg N ha^{-1} was applied at crop seeding in early May ($P< 0.01$); this result was not observed at the higher rate of 120 kg N ha^{-1}. For the 90 kg N ha^{-1} treatments, the differential effect of fertigation on generating higher N_2O production can be clearly explained by a higher soil nitrate concentration at the beginning of the incubation

period (*P* <0.01), such differences in N substrate availability were not observed across the two 120 kg N ha^{-1} treatments. The strong driving role of nitrate on N_2O production was also corroborated by a linear regression for our entire dataset (n=120; $P < 0.001$). Additionally, the effect of UAN fertigation on N_2O production across the two N rates could also be attributable to differences in the sizes of plant N sink (as suggested by yield data) at the time of the fertigation across the two split N treatments, implying lower magnitude of fertilizer-N uptake by the crop under the 60-30 split fertilization than under the 90-30 split fertilization management. Our incubation did not capture N_2O production within the entire growing season, and hence, early spring fluxes that can occur following fertilization at crop seeding, which are crucial to the annual cumulative flux during the year, are not represented in this study. The narrow range of moisture treatments applied in our study had no significant effect on the production of N_2O; it is expected that more extreme moisture increases (e.g., such as a simulation of irrigation event followed by major rainfalls) would induce pronounced denitrification conditions leading to large fluxes.

3.2 Introduction

Nitrous oxide (N_2O) is a greenhouse gas (GHG) that has a global warming potential 298 times greater than carbon dioxide and is a major contributor to the depletion of the ozone layer (Myhre et al. 2013). Agricultural soils produce 3.5 Tg of N_2O-N per year (IPCC, 2006) and in Canada, agricultural soils make up 70% of this anthropogenically produced N_2O (Kebreab et al., 2006). The use of synthetic nitrogen fertilizers in agriculture contributes significantly to this amount as a proportion of added N fertilizers are emitted as N_2O gas (Johnson et al., 2007). The use of irrigation can also increase the amount of N_2O produced in cropping systems by increasing soil moisture which in turn increases microbial activity and if soil moisture is increased enough, creates anoxic soil conditions which can lead to even higher production of N_2O (Trost et al., 2013). Many farms in Canada, particularly in Southern Alberta, are dependent on these nitrogen inputs and irrigation systems to maintain high yields for food production; however, using these management practices can be detrimental to the environment in part due to the increases in associated N losses, and hence, methods to reduce these impacts of agriculture on N_2O emissions are necessary to maintain a sustainable agricultural system.

Nitrogen fertilizers used in agriculture can be applied in available forms such as ammonium (NH_4^+) and nitrate (NO_3^-) which can be readily taken up by plants or they can be applied in unavailable forms such as urea which first needs to be hydrolyzed to NH_4^+ by the urease enzyme before they are available for plant uptake (Farquharson and Baldock, 2008). Once in the soil, this available N, if it is not taken up by plants, can be lost as N_2O through two main microbial processes, nitrification and denitrification (Firestone and Davidson, 1989). Nitrification is an aerobic process in which NH_4^+ is oxidized to hydroxylamine (NH_2OH), nitrite (NO_2^-), or NO_3^- while denitrification occurs in anaerobic conditions and is the reduction of NO_3^- to NO_2^-, nitric oxide (NO), N_2O and dinitrogen (N_2) (Bremner, 1997; Farquharson and Baldock, 2008). N_2O production in nitrification occurs when NO_2^- or NH_2OH are oxidized (Butterbach-Bahl et al., 2013). However, recent research has found that both nitrification and denitrification processes do not necessarily occur only in aerobic and anaerobic conditions (Hernandez-Ramirez et al., 2009; Stevens et al., 1997; Wolf and Russow, 2000) rather these N transformations can take place simultaneously regardless of oxygen status making it difficult to partition nitrification and denitrification sourced N_2O. Major pulse productions of N_2O are usually attributed to denitrification, which are largely dependent on discrete events triggered by increases soil water due to abundant rainfall or irrigation (Butterbach-Bahl et al., 2013). Along with soil water, other controlling factors on soil processes associated with N_2O fluxes include temperature, mineral N concentrations, organic matter, aeration, texture, and pH (Butterbach-Bahl et al., 2013; Dobbie et al., 1999; Jamali et al., 2016). Nitrogen substrate availability in particular is expected to control soil N_2O production in irrigated soils due to enhanced decomposition and mineralization, nutrient mobility in the soil as well as the propensity for anoxic conditions to occur as mentioned above. Nevertheless, the linkages between N input and availability, prevalent moist soils due to irrigation and the resulting N_2O fluxes have not been fully discerned and documented in the literature.

Irrigation can generate modest soil moisture fluctuations multiple times within a growing season; soils become wet after major rainfall or irrigation applications, and then gradually dry through plant uptake, movement of water into or out of the soil profile (infiltration, drainage and percolation, or surface runoff), and through evapotranspiration. Common irrigation practices in croplands replenish water content back to field capacity long before the available water for plants is fully depleted, thus maintaining soil moisture consistently high with small fluctuations.

Conversely, extreme variations in moisture due to irrigation timing, frequency and the intensity of water inputs can lead to increased N_2O production (Beare et al., 2009; Borken and Matzner, 2009; Ruser et al., 2006), but these moisture effects on N availability and associated N_2O production could be managed proactively through optimizing irrigation. For instance, Borken and Matzner (2009) indicated that soil N mineralization can be increased by prolonging the periods of wet soil condition (shortening drying phase) or by amplifying the wetting intensity. It is noteworthy that common watering practices in most irrigated lands suppress such extreme wetting and drying fluctuations by frequent irrigation scheduling (~ every few days or weeks), and instead, soils are kept moist with the aim of supporting optimal plant growth. Such moist conditions could hypothetically lead to overall high N_2O emissions if N substrate is not limiting.

Implementation of fertigation to apply soluble fertilizers mixed with the irrigation water can also influence N_2O emissions from agricultural systems (Fentabil et al., 2016a). Drip or sprinkler irrigation equipment can apply the fertilizer-enriched water to the already-growing plants at any time of the year because they do not damage the plant canopy, and therefore it is a suitable method of splitting fertilizer application into smaller doses rather than applying all N fertilizer at once. Multiple in-crop N applications of N may reduce the N_2O produced because N fertigation can be applied to match more closely the time when plants require nutrients (Grant et al., 2012). Matching plant uptake is important because mineral nitrogen present in the soil, if it is not taken up by plants, is vulnerable to immobilization or loss through ammonia volatilization, nitrate leaching or emissions of N_2O or dinitrogen gas (Grant et al., 2012); therefore, it can be beneficial to limit and delay the N input and available N in the soil until the crop requires it, reducing the risk of losses that are detrimental to the environment.

Adequate management of irrigation and fertilizer application could be useful in reducing N_2O emissions in semi-arid agriculture. However, little research has been conducted on the combined effects of both split N fertilization using fertigation and the moisture fluctuations associated with irrigation scheduling. Only a few existing studies have examined the combined effects of irrigation and fertilization (as fertigation), and they have focused only on drip irrigation (Abalos et al., 2014; Fentabil et al., 2016a; Fentabil et al., 2016b; Kennedy et al., 2013; Trost et al., 2014), while studies evaluating the effects of sprinkler irrigation on moisture and nitrogen availability while using split N fertilization applications and their potential impacts on N_2O emission are still lacking in the literature (Beare et al., 2009; Borken and Matzner, 2009; Ruser et al., 2006). Sprinkler irrigation typically uses a higher watering intensity rate than drip irrigation, and hence, a higher risk for N_2O emission might be posed by sprinkler irrigation systems. There is a clear paucity of knowledge regarding these potential detrimental effects of N fertigation when using sprinkler systems.

To test the effects of N fertilizer additions at various rates, in-crop fertigation using sprinklers and various moisture regimes (that represent common irrigation events) on N_2O production, a controlled laboratory study was conducted using soil samples taken from wheat (*Triticum aestivum*) field experimental plots. The objectives of this study were: i) to determine how the field-applied N fertilization at various rates impacts soil N_2O production, ii) to examine how splitting the total N fertilization into an application at crop seeding plus an in-crop fertigation affects the soil N substrate availability and associated N_2O emitted when compared to applying the entire N rate all at crop seeding, and iii) to examine how soil moisture regimes that simulate irrigation events followed by weak or moderate drying phases can interact with N fertilization management to affect N_2O emissions.

3.3 Materials and Methods

3.3.1 Experimental Design

Soils for this laboratory incubation were collected on 16 June 2016 from field experimental plots located at the Alberta Agriculture and Forestry and Research Centre located east of the city of Lethbridge, Alberta, Canada (49.41218º N, 112.45172º W). The sampled plots were used in the 2016 growing season for a fertigation field experiment (as described in Chapter 2) that had been planted to red hard spring wheat (*Triticum aestivum* cv. Carberry) on 5 May 2016. Soils at the field site are moderately fine textured Chernozems developed on water laid sediments. The soil had a sandy clay loam to loam texture (457 g kg^{-1} sand, 285 g kg^{-1} silt, 258 g kg^{-1} clay as determined by hydrometer method), a bulk density of 1.49 g cm^{-3}, an organic carbon concentration of 20.4 g C kg^{-1} soil, total nitrogen of 1.6 g N kg^{-1} soil, and a C:N ratio of 13 (as measured by dry combustion). The site has a 30-year average (1971-2000) annual precipitation of 386.3 mm and annual average temperature of 5.7 °C (Environment Canada 2017).

The field treatments were arranged as a blocked, split-plot design with the fertigation treatment applied to the main plot (fertigation or no fertigation) and different nitrogen fertilizer rates added during seeding at the sub-plot level. Each treatment was replicated twice in two blocks (n= 4 plots per field treatment). The complete experiment includes 30 treatments with multiple N rates and timings; we selected and sampled a subset of five field treatments for this controlled study: 90 and 120 kg N ha^{-1} all added at crop seeding (no fertigation), 60 and 90 kg N ha^{-1} at seeding plus another 30 kg N ha^{-1} added through fertigation and the control with no fertilizer added. To make comparisons of the fertigation treatment, the total N rate of the applied fertilizer equaled 90 or 120 kg N ha^{-1} added during the entire growing season. The fertilizer added simultaneously with seeding was side-banded granular urea (3.5-5cm horizontally from the seed and 0-2.5 cm deep) and was applied on 5 May, while the fertigation fertilizer consisted of a liquid urea-ammonium nitrate (UAN) applied at a rate of 30 kg N ha^{-1} at the wheat tillering leaf stage on 7 June. The irrigation system was a lateral roll sprinkler which used a calibrated fertilizer injection pump to add the UAN to the water and applied 12 mm of the fertigation water in one pass to the fertigation blocks, then once the system was flushed with regular water, the sprinkler made a separate pass to apply the same rate of regular irrigation water (12 mm) to the unfertigated plots. Irrigation water was applied throughout the growing season in equal amounts across all the treatments to ensure that water was not yield limiting and it was sourced from the St. Mary River Irrigation System.

Soil samples for our incubation were collected from the field site on 16 June 2016. To ensure that representative field samples were taken, the soil was sampled from four random locations within the center of each plot and away from the outer 2 rows to prevent any biases of the edge row positions. Litter and standing stubble was scraped away from the surface and a shovel was used to take four soil subsamples per plot from the 0-15 cm depth increment, in the interrow position, which was one-third of the distance between adjacent wheat rows, and subsequently, the samples were composited by plot. Rocks and plant material were removed and approximately 1 kg of the bulked sample was placed in a labelled plastic bag and stored at 5°C in a cold room until preincubation.

3.3.2 Water Retention Measurements and Moisture Treatments for the Incubation

One undisturbed soil core sample (80 cm diameter; HYPROP™, UMS, Germany) was also taken from each plot in an interrow position (n= 20) at the 5-10 cm soil depth increment. The top 5 cm was excavated using a shovel to remove any plant litter and root material and to avoid any soil surface crusting and excessive dryness. Upon collection, the soil cores were covered with plastic lids, placed into plastic bags, wrapped in bubble wrap and stored at 5°C. These were used to determine the bulk density and the soil moisture retention curve using the HYPROP™ System as described in Hebb et al. (2017). Based on the results of the water retention curve, field capacity (-33 kPa water potential) and permanent wilting point (-1500 kPa) were estimated. The field capacity minus permanent wilting point was used to determine the plant available water. Water content at field capacity was 0.28 cm^3 cm^{-3}, which corresponds to 64% water filled pore space (WFPS) and at permanent wilting point was 0.19 cm^3 cm^{-3}, which corresponds to 44% WFPS, and hence the plant available water within these boundaries was 20% WFPS. A typical management allowable depletion (MAD) of the plant available water in Alberta irrigation systems for hard red spring wheat is 40% (having still 60% of plant water available in the soil profile before irrigation takes place). This conservative irrigation approach supports optimum conditions for crop growth as these fluctuations of water contents are small (ARD, 2011). Therefore, three moisture treatments were selected and applied in our incubation to test and simulate the effects of a typical range of irrigation events as follows:

- a constant moisture control treatment was kept consistent at 60% WFPS.

- a weak drying treatment where water content was initially increased to a field capacity of 64% WFPS and experienced drying to 56% WFPS (which corresponds to 60% of plant available water still remaining in the soil), and
- a moderate drying treatment where water content was initially increased to a field capacity of 64% WFPS and experienced drying to 50% WFPS (which corresponds to 30% of plant available water still remaining in the soil).

The resulting wet-drying fluctuations in our study were not extreme but resulted in relatively small moisture differences (Fig. 3-1a) as they aim to represent changes in water contents that simulate typical irrigation management in annual croplands as mentioned above. These irrigated cropping systems unlikely experience excessive wetting and drying changes but instead moist conditions conducive to optimum plant growth are most common.

The percent WFPS was determined using the following equations:

$$\%WFPS = \left(\frac{\theta_v}{TP}\right)(100) \quad [1]$$

$$\text{where } \theta_v = \text{percent volumetric water content} = (\%\theta_m)(P_B), \quad [2]$$

$$\text{and TP} = \text{percent total porosity} = \left(1 - \frac{P_B}{P_P}\right)(100), \quad [3]$$

$$\text{where } P_P = \text{soil particle density} - \text{ assumed to be } 2.65 \left(\frac{\text{Mg}}{\text{m}^3}\right),$$

$$P_B = \text{soil bulk density } (\text{Mg/m}^3)$$

3.3.3 Incubation, Gas Sampling and Laboratory Analyses

Prior to the beginning of the incubation period, a 2-day preincubation was initiated at room temperature (20°C). After preincubation, each of the 20 bulked soil samples were mixed, coarse fragments were removed, and large aggregates were broken up by hand. Then, from each of the

20 samples, 6 subsamples (2 subsamples for each water regime) of 120 g of soil (on oven-dried basis) was placed into 118 cm^3 labelled plastic containers and packed to a bulk density of 1.30 Mg m^{-3} for a total of 120 microcosms. The area of soil surface in each microcosm was ~21.2 cm^2. To regulate the rate of water loss, each microcosm was capped with a plastic lid with holes.

As the samples air dried, the constant moisture controls were weighed daily and room temperature deionized water was added to keep the water content consistent at 60% WFPS. The weak and moderate moisture treatments were also weighed daily to record the gradual drying and once the lower threshold of water content (56% or 50% WFPS) was reached, an irrigation event was simulated and deionized water was added to the soil to replenish the water content to field capacity (64% WFPS as identified from the soil water retention curve at -33 kPa water potential). The added water was distributed evenly and gently on the soil surface minimizing any impact damage or changes in the soil structure or crust formation. The incubation was conducted until at least two successive moisture phases were simulated (Fig. 3-1a). Gas sampling was done twice a week for 5 weeks on days 2, 5, 8, 11, 15, 18, 21, 25, 29, and 32.

On the dates of gaseous flux sampling, each microcosm was placed into a 500 mL Mason jar fitted with a rubber septum which acted as a chamber. Gas sampling occurred 15, 30 and 45 minutes after the lids were placed on the jars. For each gas sample, a 20 mL syringe with a #20 needle was used. First the syringe was flushed twice with ambient air from the room then the needle was placed into the rubber septum located on the chamber lid and flushed twice with air from inside the chamber before a full syringe of chamber gas was extracted. The needle was then inserted into an evacuated 10 ml Exetainer® vial (Labco, UK), and the gas sample was pushed into the vial. These steps were repeated for all 120 microcosms. The 120 microcosms were split into 3 groups during gas sampling: 45 in the first 2 groups and 30 in the last group for ease of sampling and pair of ambient air samples was taken, once at “time zero”, when the first lid was placed on the first chamber body for each of these groups for a total of 6 ambient samples per day. The filled vials were kept in cold storage (5°C) before analysis. Samples were analyzed for concentrations using a gas chromatograph (Thermo Fisher Scientific Trace 1310 Gas Chromatography) equipped with an electron capture detector to measure N_2O concentration and a autosampler (CTC Analytics Combi PAL auto sampler). The daily N_2O flux of each chamber was determined by fitting a linear or quadratic curve between the average ambient N_2O measurements from that day along with the three N_2O measurements from the chamber versus time (Lin *et al.*, in press). A test was performed to determine the existence of outliers for each flux calculation by finding the lowest possible R^2 value with each combination of 3 of the 4 fluxes. If an outlier was found this value was removed and the flux calculation was performed using 3 values instead of 4. Using an alpha value of 0.20, zero flux was determined if there was no significant relationship. If the relationship was significant, the ideal gas law was used to calculate the flux. The equation used was:

$$N_2O\ Flux = \frac{S \times P \times V}{M \times R \times T} \quad [4]$$

where N_2O flux is the production rate of N_2O ($\mu g\ N_2O\text{-}N\ g^{-1}$ soil min^{-1}); S is the slope of the line from either the simple linear regression or the first-order derivative at time zero from the quadratic curve ($\mu L\ L^{-1}\ sec^{-1}$) (Pennock et al., 2010; Yates et al., 2006); P is the gas pressure (atm); V is the headspace volume of the chamber (L) after subtracting the soil volume (0.5 – 0.092 = 0.41 L); M mass of the soil in the microcosm (g); R is the gas constant (atm $\mu L\ K^{-1}\ \mu mol^{-1}$) and T is the temperature of the gas (K). We recorded that the fluxes were 43, 4 and 53% linear, quadratic and zero regressions, respectively. The estimated minimum N_2O flux detection limit using our method was 0.088 ppmv. For this detection limit estimation, we followed a conservative approach by considering three times the standard deviation of repeated concentration measurements (n= 30) of standard gas samples with a known concentration of N_2O (0.25 ppm N_2O) (Lin *et al.*, in press). To calculate the cumulative emissions between two consecutive sampling dates, the product of the average N_2O flux rate and the time interval between the two sampling dates was used.

We analyzed all our soil samples prior to and after the incubation period for ammonium (NH_4-N) and nitrate (NO_3^- -N). The 2 M potassium chloride method was used to extract NH_4-N and NO_3^- -N at a ratio of 10:1.

3.3.4 N

3.3.4 N_2O Emission Factor

N_2O emissions can be reported as an emission factor (EF) of applied N-fertilizer rate. The N_2O emission factor was calculated by subtracting the cumulative production of the 0 kg N ha^{-1} control treatment from the cumulative production of the fertilizer treatment (90 or 120 kg N ha^{-1}) then dividing by the total applied N rate as described by the IPCC (2006) Tier I methodology:

$$N_2 0\ EF\ (\%) = \frac{N_2O\ \text{production}_{N\ treatment} - N_2O\ \text{production}_{0\ \text{kg N ha}-1\ control}}{total\ N\ \text{fertilizer}\ input} \times 100 \qquad \textbf{[5]}$$

3.3.5 Statistical Analysis

The N_2O emission data was analyzed for daily and cumulative fluxes. The Shapiro-Wilk test was used to test for normality and the Bartlett test was used to determine homogeneous variance. If the assumption of normality was not met, a Box-Cox Power transformation was used to account for non-normality. If logarithmic transformation was needed, an offset constant was added to the data values to ensure positive data was available to conduct this transformation procedure. One-way ANOVA's and post hoc comparisons were done using Tukey's Honest Significant Difference tests to assess the effects of increasing fertilizer rate without fertigation compared to the control, to test the effects of fertigation versus no fertigation, and the moisture treatments on cumulative N_2O production, and to test for differences in daily N_2O emissions during the experiment. An alpha critical level of 0.05 was used and all tests were done using R software, version 3.3.1.

3.4 Results

3.4.1 Cumulative N_2O Fluxes - Fertilizer Management Effects

We explored potential relationships of soil N_2O production as a function of N fertilizer addition and rates, and found no consistent patterns in part due to the overwhelming data variations (the coefficient of variation for the whole N_2O flux data set for cumulative emissions was 229% (n=120)). Although mean N_2O fluxes seemed to increase with N fertilizer rate, there were no significant differences in cumulative N_2O fluxes when comparing the 0 kg N ha^{-1} control (1.06 μg N g^{-1} soil), versus the 90 kg N ha^{-1} without fertigation treatment (1.84 μg N g^{-1} soil) or the 120 kg N ha^{-1} without fertigation treatment (4.79 μg N g^{-1} soil) based on a one-way ANOVA (Table 3-1 and Fig. 3-2). Likewise, a linear regression analysis was conducted for N_2O production on both untransformed and transformed data as a function of total N fertilizer rate when no fertigation was applied, and indicated that this relationship was weak and not significant (P=0.46 for transformed data) with a low goodness of fit (R^2=0.008) (Fig. 3-3).

To test the effects of fertigation on N_2O production, we compared fertigation vs. no fertigation within each of the two treatments with equal total added N fertilizer. A one-way ANOVA contrasting fertigation vs. no fertigation at the 90 kg N ha^{-1} rate revealed that there was a strong significant effect of fertigation on N_2O production (P= 0.007) with more N_2O being produced because of the recent in-crop fertigation (7.39 ± 2.00 μg N g^{-1} soil) compared to the unfertigated soils (1.84 ± 0.87 μg N g^{-1} soil) (Table 3-1 and Fig. 3-4). Contradictorily, the comparison of fertigation vs. no fertigation for the higher total rate of 120 kg N ha^{-1} showed no significant effects on N_2O production as a function of the fertigation (2.63 vs. 4.79 μg N g^{-1} soil, respectively) (Table 3-1 and Fig. 3-4).

3.4.2 Cumulative N_2O Fluxes - Moisture Fluctuations

The three moisture treatments applied during the incubation were compared using a one-way ANOVA, and we found no significant effect on N_2O production for the cumulative flux (P= 0.397) (Table 3-1), or for any individual flux sampling date. Although the weak drying treatment tended to have a numerically higher cumulative flux (5.36 µg N g^{-1} soil) than the soil microcosms under both constant WFPS (2.90 µg N g^{-1} soil) and the moderate drying treatments (2.36 µg N g^{-1} soil), these were not statistically different. Overall, most of the dynamics of N_2O production occurred within the first week of the 32-day incubation (Fig. 3-1b); a period when the applied moisture treatments (weak drying and moderate drying) had not differed yet (Fig. 3-1a). Therefore, instead of an effect of moisture treatments, this early N_2O production could be interpreted as accelerating microbial utilization of the initial mineral N substrate existing in the soils at the beginning of the incubation.

3.4.3 Emission Factor of N_2O Production

The N_2O emission factor (Eq. [5]) was calculated for each combination of N fertilization rate and fertigation. The EF for soils receiving a total rate of 90 kg N ha^{-1} were strikingly as high as 7.0% when fertigation was applied and one order of magnitude lower (0.9%) under no-fertigation management (i.e., all N fertilization applied at crop seeding). After performing the Kruskal-Wallis Test the difference between the EF of fertigated and unfertigated treatments was found to be significant at the 90 kg N ha^{-1} rate. On the other hand, when a total rate of 120 kg N ha^{-1} was applied, fertigation and no fertigation resulted in more similar EFs with 1.3 and 3.1%, respectively and was not found to be significant after preforming the Kruskal-Wallis Test.

3.4.4 Soil Mineral Nitrogen Patterns

Certain differences in mineral nitrogen measured in soils prior to the laboratory incubation were observed across N fertilization treatments (Table 3-2). Concentrations and changes in NH_4^+ concentrations were small across the various N treatments; this can suggest rapid nitrification took place under predominant aerobic conditions across all soil microcosms. In contrast, NO_3^- results revealed clear differences as a function of N management. Prior to initiating the incubation, the concentration of NO_3^- was the lowest in the 0 kg N ha^{-1} control, as anticipated, and there was in general more NO_3^- in the treatments which had recently received fertigation (fertigation took place 9 days before the soil sample collection). After the incubation, the concentration of nitrate increased by roughly 10 mg N kg^{-1} soil in all of the treatments, with the 0 kg N ha^{-1} control still remaining the lowest. With the aim of comparing the effect of fertigation on soil nitrate concentrations prior to the beginning of the incubation, one-way ANOVAs were performed between the fertigated and non fertigated treatments within the 90 and 120 kg N ha^{-1} rates separately. When fertigation was used at the total rate of 90 kg N ha^{-1} (i.e., 60-30 split), there was significantly more NO_3^- available in the soil compared to when all of the 90 kg N ha^{-1} rate had been applied at crop seeding in early May ($P < 0.05$; Table 3-2). On the other hand, no significant effect of fertigation was found when comparing between the two treatments receiving a total fertilizer rate of 120 kg N ha^{-1}. Furthermore, given the observed differences in nitrate concentrations across N managements and in particular for fertigation vs. no fertigation, we examined the relationship between N_2O production and nitrate concentrations via regression analyses using our entire dataset (n= 120; Fig. 3-5). A clearly significant linear regression was found for cumulative N_2O production as a function of soil nitrate concentration at the beginning of the incubation (p= 0.004) although it can be noted the goodness of fit was modest, in part perhaps because flux data is highly variable by nature and also because of the existence of several other interacting factors that influence soil N_2O fluxes as mentioned above.

3.5 Discussion

3.5.1 Effects of a Recent In-crop N Fertigation on Soil N_2O Production and Nitrate

In our laboratory experiment, soils collected shortly after an in-crop fertigation (30 kg N ha^{-1}) had a significantly higher N_2O production only when applied following an intermediate N rate at crop seeding (60 kg N ha^{-1}) (Table 3-1 and Fig. 3-4). Several potential explanations for this effect of 60 plus 30 kg N ha^{-1} on N_2O production are discernable. It was evident that the 60 plus 30 kg N ha^{-1} treatment produced larger amounts of N_2O and also caused the highest increase in initial nitrate concentration in the soils after fertigation (Table 3-2). This greater N availability accounts, in part, for the larger N_2O production under this split N management. It is also clear that neither the full N rate of 90 kg N ha^{-1} applied earlier at crop seeding nor a higher N rate at seeding combined with fertigation (90 plus 30 kg N ha^{-1}) yielded such a strong increasing effect on N_2O production and N availability as was generated by the 60-30 N split. In these irrigated fields, additions of N fertilizer early in the growing season as 90 kg N ha^{-1} at the time of seeding can result in gaseous N losses (e.g., ammonia, dinitrogen, or N_2O) or temporal N immobilization in the soil because the crop canopy and nutrient uptake capacity is just beginning to gradually develop in May. High fertilization rates applied at seeding did not match plant uptake because the crops have not emerged or were small and did not require or were not capable of high rates of nutrient uptake (Grant et al., 2012). If not taken up by plants, such nutrient becomes vulnerable to soil immobilization or loss through volatilization, leaching or biological N emissions (dinitrogen, N_2O).

With respect to the differential effect of fertigation on N_2O production across the two N rates (90 vs. 120 kg N ha^{-1}), the fact that splitting N fertilization with 90 kg N ha^{-1} applied at seeding plus 30 kg N ha^{-1} applied via fertigation did not raise soil N_2O production and N availability (as it did for the 60-30 split) could be also attributable to differences in the size of plant N sink at the time of the fertigation across the two split N treatments, perhaps leading to a disproportionally lower vegetative size and associated fertilizer-N uptake by the crop under the 60-30 split fertilization than under the 90-30 split management at time of fertigation. Harvested grain yield was 4207 kg dry matter ha^{-1} for the 60-30 split, while it was 4455 kg dry matter ha^{-1} for the 90-30 split (data not shown; see harvested grain data in Chapter 2). This could support the hypothesis that a larger sink capacity is a response to increasing N fertilization early in the season. The relationship between higher N uptake as a function of larger plants was reviewed by Lemaire et al. (2007). After analyzing multiple studies in which soil N supply was nonlimiting, they found that with wheat, N uptake increased linearly with above ground biomass and plant leaf area indicating that with high levels of N availability in the soil (up to root uptake capacity), plants will grow larger, and this larger plant size will progressively feedback into even greater N removal from the soil as the plant N uptake continues accelerating. Applying this postulate in our study, the relatively smaller plants from the split fertigated 60-30 kg N ha^{-1} would have been likely unable to take up the additional 30 kg N added via fertigation due to their smaller size (reduced sink capacity), compared to the larger plants with higher initial fertilizer, leaving the N vulnerable to loss as N_2O during the first stages of the incubation period.

The fertigated 90 kg N ha^{-1} soils showed the largest flux of N_2O in the initial stages of the incubation. Comparing the fertigation vs. no fertilization at a total rate of 90 kg N ha^{-1}, N_2O production from the fertigated soils was roughly one order of magnitude larger in particular during the first week of the incubation (Fig. 3-6). As mentioned above, the recent UAN fertigation and the associated higher initial nitrate concentration can account for these larger early N_2O fluxes under the 60-30 split fertilization-fertigation.

It is expected that high N fertilization at crop seeding in early May could have led to large soil N availability and associated N_2O production at that early stage of the growing season in part due to high N fertilizer input and the lack of crop N uptake in the beginning of the growing season. However, our incubation reflects field N management at one point in time when our field soil collection was conducted in mid June, and hence, our study does not integrate whole seasonal effects because it only captured the soil status shortly after the early-June fertigation (i.e., the soil collection was nine days after the fertigation). It can be hypothesized that early in the growing season (~ mid May), N_2O losses could have been high in the unfertigated soils that receiving the full N dose at seeding. In related work (Chapter 2 of this thesis); field measurements of N_2O emissions clearly support this assertion as major pulses of N_2O fluxes occur in these unfertigated fields from 20 May to 9 June 2016. Such soil N transformations and associated gaseous losses may have been responsible for the lower concentration of mineral N in the soils receiving N fertilization only at seeding, subsequently resulting in lower N_2O fluxes during the incubation. Future studies can examine soil N transformations and N_2O production early in the growing season, which seem crucial to quantifying, understanding and managing the annual cumulative flux.

3.5.2 Nitrogen Substrate Availability driving N_2O Production

Substrate N availability in the collected soils were shown to trigger and drive high N_2O production (Tables 3-1 and 3-2; Fig. 3-5). A consistent linkage between N_2O production and nitrate concentration can be explained between two key processes controlling nitrate dynamics (i.e., nitrification and denitrification) and leads to N_2O production in soil systems. At the same time, nitrification and denitrification rates are controlled by soil properties such as texture, organic matter quantity and availability, bulk density, moisture and temperature, and also concentration of inorganic N (Butterbach-Bahl et al., 2013; Dobbie et al., 1999; Jamali et al., 2016). In our study, since nitrate continued accumulating from the beginning to the end of the incubation period (Table 3-2) and based on the occurrence of the largest N_2O fluxes in the initial phase of the incubation (Figs. 3-1b and 3-6), it can be deduced that both nitrification and denitrification were active in the incubated soils and these two processes simultaneously generated N_2O. Furthermore, the increasing nitrate concentrations in all soils demonstrates that nitrification was rapidly occurring, and hence, there was sufficient substrate for denitrification, but that the anaerobic conditions required for triggering a large N loss via denitrification were not reached (Mosquera et al., 2006).

As suggested above, soil N immobilization under excessive-N addition scenarios in the early season could also have interplayed in restraining higher N availability for N_2O production under the high N fertilizer rates, including 90 and 120 kg N ha^{-1} added at seeding. Conversely, the fertigated soils had 30 kg N ha^{-1} of UAN applied 9 days just prior to field soil collection. From the UAN addition, the ammonium and nitrate would likely have been readily used by the crop before soil collection depending on the plant uptake capacity, but the urea component of the UAN would have been undergoing hydrolysis into ammonium and subsequently nitrification (Mobley et al., 1995). Therefore, due to the various N forms present in UAN, it was expected that N transformation processes were fast, but taking placed at several stages simultaneously.

3.5.3 N Fertilizer Rate, Soil Moisture and N_2O Emissions

Earlier studies frequently report larger N_2O production with increasing N input. Linear (Bouwman, 1996; Dobbie et al., 1999; Grant et al., 2004; Jamali et al., 2015) and nonlinear (Bouwman et al., 2002; Kim et al., 2013) response modes of N_2O production to N fertilizer input have been identified. Bouwman et al. (2002) and Kim et al. (2013) described that N_2O emissions can remain relatively non-responsive across an intermediate range of N input rates; however, emissions abruptly increase when a certain threshold is reached and surpassed. In principle, under N-limiting conditions, available N present in the soil can be avidly used by plants or microbes; therefore, only if the amount of N in the soil is excessive for plant uptake would the exceeding N likely be used by microbes and probably lost as N_2O. Thus, when there is an increase in N fertilizer above plant uptake requirements, N_2O production should also increase. However, as noted above, in our incubation study, no linkage was found for N_2O production as a function of N input (Fig. 3-3) perhaps because the assessed N rates were in general not exceeding the plant N requirements at the time of soil collection in the experimental site. Conversely, in related work (Chapter 2 of this thesis); field measurements of cumulative N_2O flux at the same experimental site assessing a large set of N rates and encompassing the entire growing season revealed a consistent linear relationship between N_2O emission and increase N fertilizer [N_2O emission (μg N ha^{-1}) = 110.78 + 2.57 x N rate (kg N ha^{-1}); $p < 0.001$; $R^2 = 0.52$].

Certain inherent limitations of incubation studies can be noted. Disturbance of soil structure and aggregates due to field sample collection and preparation (including breaking up aggregates), and soil re-packing into incubation containers, may have deviated soil microcosms from field conditions. In addition, laboratory incubations typically provide consistent, optimum conditions of temperature and moisture. Collectively, soil microcosms can differ from *in situ* soil profile with respect to air permeability and gas diffusion as well as the proportion of large vs. small pores which can lead to formation of anaerobic microsites for increased denitrification (Mosquera et al., 2006).

The narrow range of soil moisture fluctuations in our incubation (50 to 64 % WFPS; Fig. 3-1a) represented moist conditions common under irrigation management systems in Southern Alberta. As noted above, soil nitrate accumulated due to nitrification during the incubation period (Table 3-2) under generally moist soil conditions, also indicating that denitrification was not prevalent. Hence, in our study, varying combinations of soil nitrification and denitrification in the three applied moisture regimes can have contributed to the same outcome of N_2O production, leading to a lack of consistent differences across such narrow range of moistures (Table 3-1) although with ample variability in the patterns of N_2O fluxes (Fig. 3-1b).

In our study, the rates of water input to simulate irrigation events were relatively small compared to typical water inputs that occur in *in situ* soil profiles. The weak drying treatment that represented an optimum irrigation scheduling based on a management allowable depletion (MAD) of 40 % received only 1.6 mm water to replenish the microcosms from 56 back to 64 % WFPS (3.4 mL in 21.2 cm^2 horizontal surface of the microcosm), while the moderate drying treatment received 2.8 mm water to increase WFPS from 50 back to 64 % following a MAD of 60%. In related work at the same field experiment where our incubated soils were collected (Chapter 2 of this thesis); major N_2O fluxes were only evident when at least 10 mm of water input as an irrigation or rainfall event took place. Even though the measured fluxes in the fields captured and integrated the activity from the entire soil profile (as compared to only ~5 cm height in the soil microcosms), the water inputs in the soil incubation appear to be too small to be biologically significant and effectual in changing soil N transformations across our assessed moisture regimes.

Earlier reports have shown that increasing soil moisture increases the production of N_2O in orchards (Fentabil et al., 2016a; Fentabil et al., 2016b), agronomic crops (Dobbie et al., 1999; Liu et al., 2011; Ruser et al., 2006) and pastures (Dobbie et al., 1999; Rudaz et al., 1989). These studies reported that the highest N_2O fluxes became evident between 48 and 90 % WFPS; it is noteworthy that all our moisture regimes are within these favorable boundaries but do not include the extremely wet WFPS, suggesting that all the moisture regimes in our incubation experiment supported favorable conditions for soil N_2O production. Based on this rationale, as water contents were not a limitation, our three moisture treatments resulted in no differences. Further research can consider comparing moisture regimes encompassing fluctuations from near saturation (> 90% WFPS), optimal moisture conditions (ranging between 48 and 90%), and extreme drying periods (up to below 25% WFPS). Such strong wet-drying cycles could represent field conditions of non-irrigated croplands in Southern Alberta following major water inputs (e.g., snow melting, large rainfall events).

3.6 Conclusion

Nitrous oxide production in our incubation was clearly increased by an in-crop N fertigation (30 kg N ha^{-1}) applied in the experimental fields few days prior to the soil sample collection, but this only occurred when an intermediate N rate had been applied at crop seeding (60 kg N ha^{-1}). Other N fertilization managements combining various N rates and timing such as adding all the N at seeding or using higher N rates did not lead to any consistent differences in N_2O production. This could be in part attributed to the high variability of the flux data in the laboratory incubation.

The same fertigation management (i.e., 60 kg N ha^{-1} at seeding plus 30 kg N ha^{-1} in early June) that increased N_2O production, also increased initial nitrate availability. Both N_2O production and nitrate concentration under this management (splitting 60-30 with fertigation) were numerically the largest magnitudes across all the assessed N managements. In fact, N_2O production and nitrate were consistently associated with each other across our cumulative data set, revealing the key driving role of substrate availability on N_2O production. We further infer that both nitrification (due to additional nitrate accumulation during our incubation) and denitrification (due to larger N_2O fluxes in the initial phases of our incubation) contributed to N_2O production. While N fertilization at crop seeding in early May would have putatively led to large soil N availability and associated N_2O production due to high N input and lack of plant uptake in the beginning of the season, our incubation does not integrate these putative early-season effects because our field soil collection in mid June only captured the soil status at that specific time, shortly after the early-June fertigation. Moreover, dynamic interactions of plant growth and N uptake with N fertilization rate prior to the time of field soil collection could explain the lack of differential effects of fertigation on N_2O production and N availability when applied at the total rate of 120 kg N ha^{-1} (90 at seeding plus 30 via fertigation); a larger plant canopy developed early under this N management would have resulted into a greater N uptake sink that could remove the recently-fertigated N from the soil.

In this incubation study, the small soil moisture fluctuations that represented a typical range of irrigation regimes did not impacted N_2O production. The fact that soil nitrate kept accumulating during the incubation period indicates that the moist soil conditions (i.e., WFPS ranging from 50 to 64%) favored nitrification, but that they were not wet enough to promote major differences in denitrification losses amongst the moisture treatments. Our study focused on simulating moisture regimes as similar to those commonly applied in well-watered croplands; future studies can focus on testing the effects of much stronger wetting-drying regimes; for instance, testing the effects several consecutive days of major spring rainfalls in the early growing season where soil would nearly reach water saturation, moisture would stay high, and plant N uptake would still be minimal, hypothetically leading to large pulse production of N_2O as a function of interactions between soil moisture and nitrogen availabilities.

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3.8 References

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3.9 Tables

Table 3-1. Cumulative N_2O emissions by N fertilization and moisture treatments in the soil incubation.

	Cumulative N_2O emissions (μg N g^{-1} soil) ± SE
Nitrogen Fertilization Treatment	
0 kg N ha^{-1}	1.06 ± 0.70
90 kg N ha^{-1} No Fertigation	1.84 ± 0.87
90 kg N ha^{-1} Fertigation	7.39 ± 2.00
120 kg N ha^{-1} No Fertigation	4.79 ± 2.46
120 kg N ha^{-1} Fertigation	2.63 ± 1.32
Moisture Treatment	
Constant	2.90 ± 1.09
Weak Drying	5.36 ± 1.74
Moderate Drying	2.36 ± 0.82
Comparisons	P- value[w]
All four fertilization treatments compared to 0 kg N ha^{-1} [x]	N.S
Moisture treatment [y]	N.S
Fertigation vs. No Fertigation 90 kg N ha^{-1} [z]	**
Fertigation vs. No Fertigation 120 kg N ha^{-1} [z]	N.S

SE stands for standard error of the mean

w *, **, *** and N.S indicate a significant treatment effect based on ANOVAs at $p \leq 0.05$, 0.01, 0.001, or no significant effect, respectively.

x Effects of N fertilization additions were tested by comparing the four N treatments against the 0 kg N ha^{-1} control using a one-way ANOVA.

y Effects of the moisture treatments were tested using the cumulative N_2O emissions from across all N fertilization treatments including the 0 kg N ha^{-1} control and tested using a one-way ANOVA.

z Effects of fertigation at both 90 and 120 kg N ha^{-1} were compared to unfertigated treatments within the same N rate using a one-way ANOVA.

Table 3-2. Average soil NH_4^+ (mg N kg^{-1}) and NO_3^- (mg N kg^{-1}) concentrations of the samples prior to and immediately after the end of the incubation experiment.

Treatment	**Prior to Incubation**[z]	**After Incubation (All moisture treatments)**	**After Incubation Constant WFPS**	**After Incubation Weak Drying**	**After Incubation Moderate Drying**
		NH_4^+			
0 kg N ha^{-1}	0.88	0.83	0.69	0.66	1.14
90 kg N ha^{-1} No Fertigation	0.74	0.84	0.89	0.70	0.89
90 kg N ha^{-1} Fertigation	0.49	1.24	1.32	1.35	1.08
120 kg N ha^{-1} No Fertigation	0.94	1.04	1.06	0.93	1.12
120 kg N ha^{-1} Fertigation	1.33	1.52	1.45	1.51	1.60
		NO_3^-			
0 kg N ha^{-1}	8.45	18.82	19.63	19.46	17.37
90 kg N ha^{-1} No Fertigation	14.22^a	24.28	25.69	24.75	22.39
90 kg N ha^{-1} Fertigation	17.33^b	28.98	28.22	29.95	28.78
120 kg N ha^{-1} No Fertigation	14.89^a	26.06	27.45	26.73	24.01
120 kg N ha^{-1} Fertigation	15.41^a	23.92	23.87	24.94	22.96

z Effects of fertigation on NO_3^- concentrations were only tested between treatments of equal total N rate prior to the incubation using a one-way ANOVA. Same letters indicate no significant differences based on Tukey HSD.

3.10 Figures

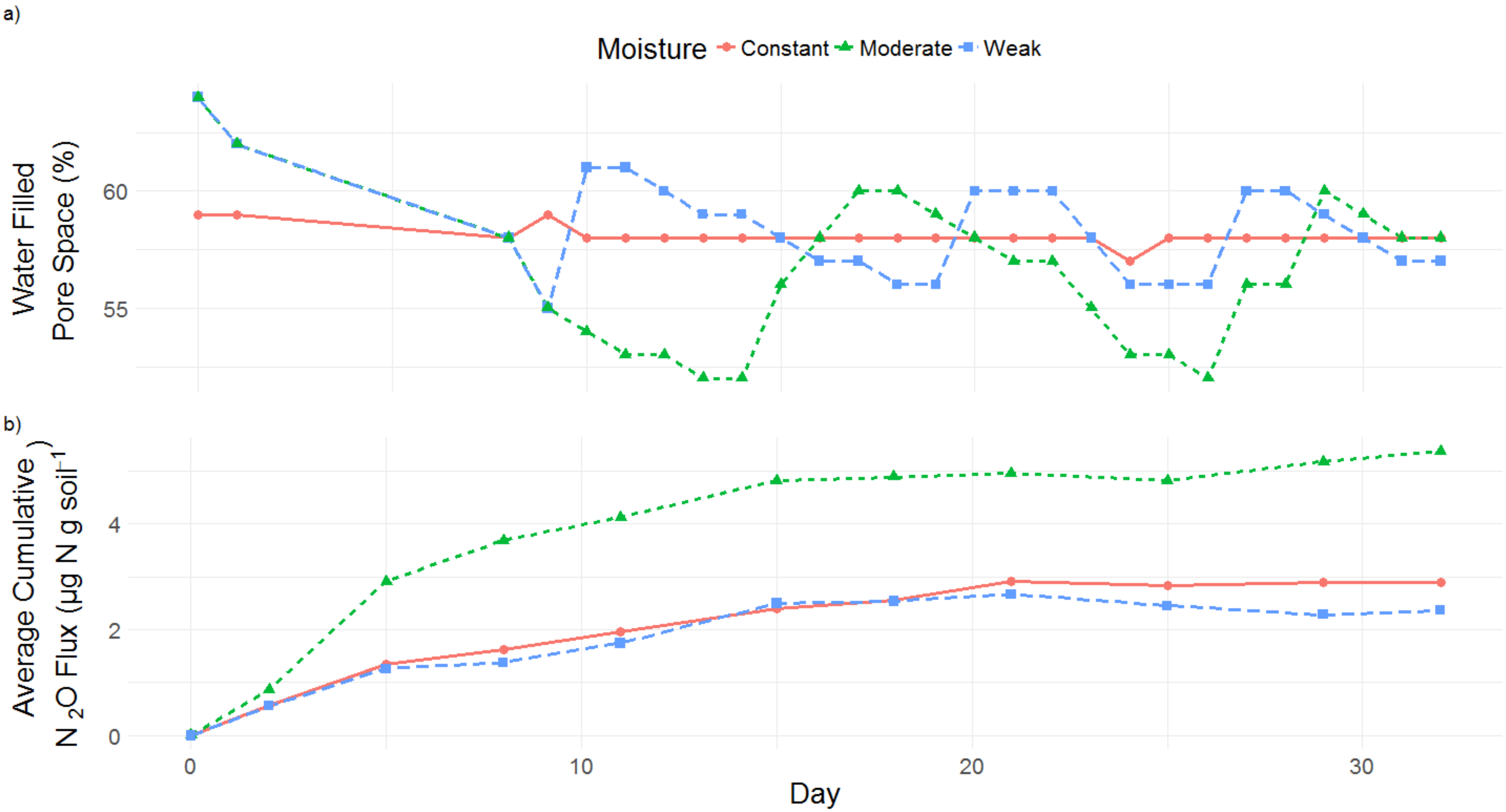

Figure 3-1. a) Water-filled pore space (%) of the incubated soils and b) cumulative N_2O flux by moisture treatment during the entire incubation period. Each moisture treatment was represented by 40 soil microcosms.

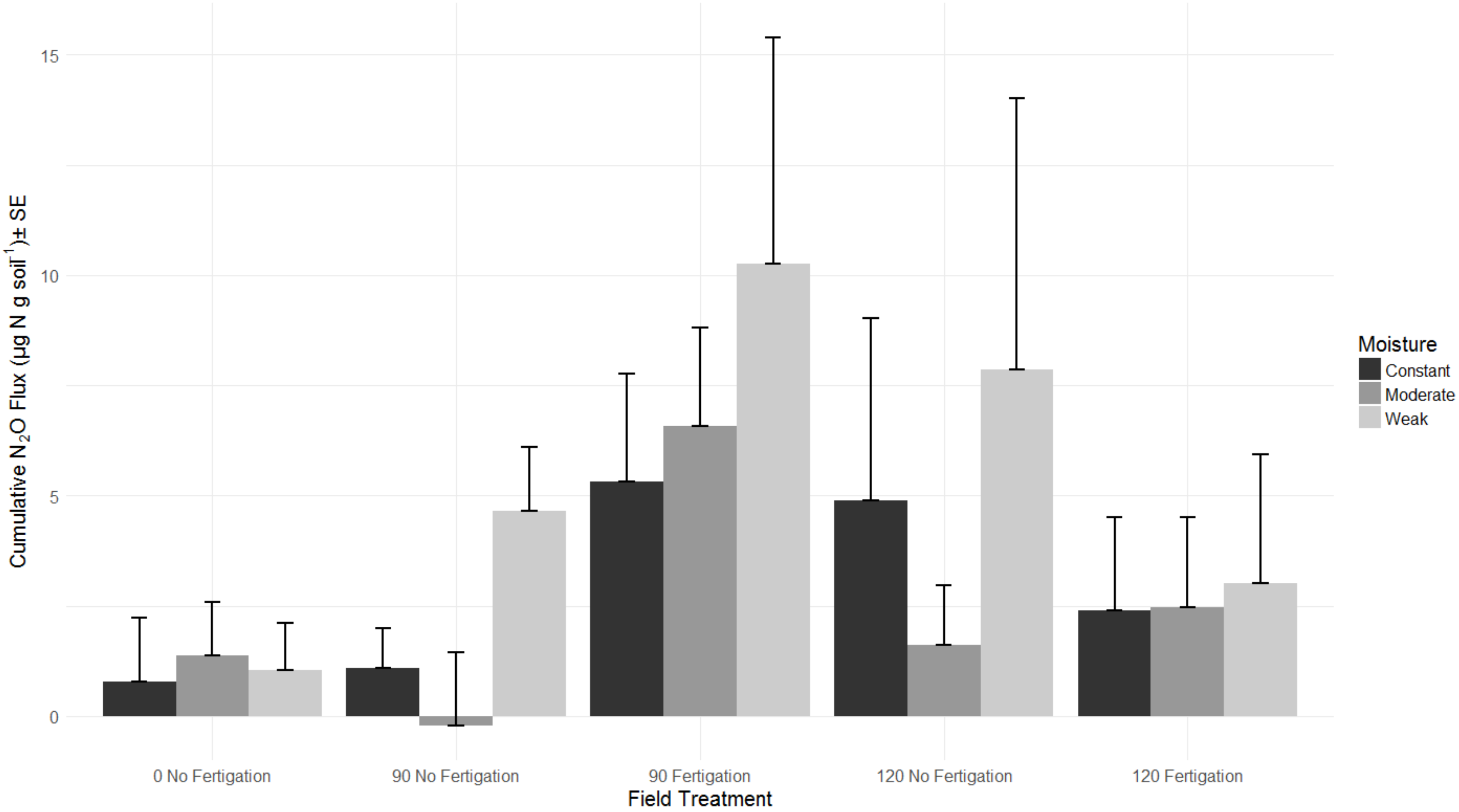

Figure 3-2. Cumulative emissions of N_2O for the duration of the laboratory incubation for each nitrogen management X moisture treatment combination. Nitrogen management and moisture treatments are listed in Table 3-1. SE stands for standard error of the mean.

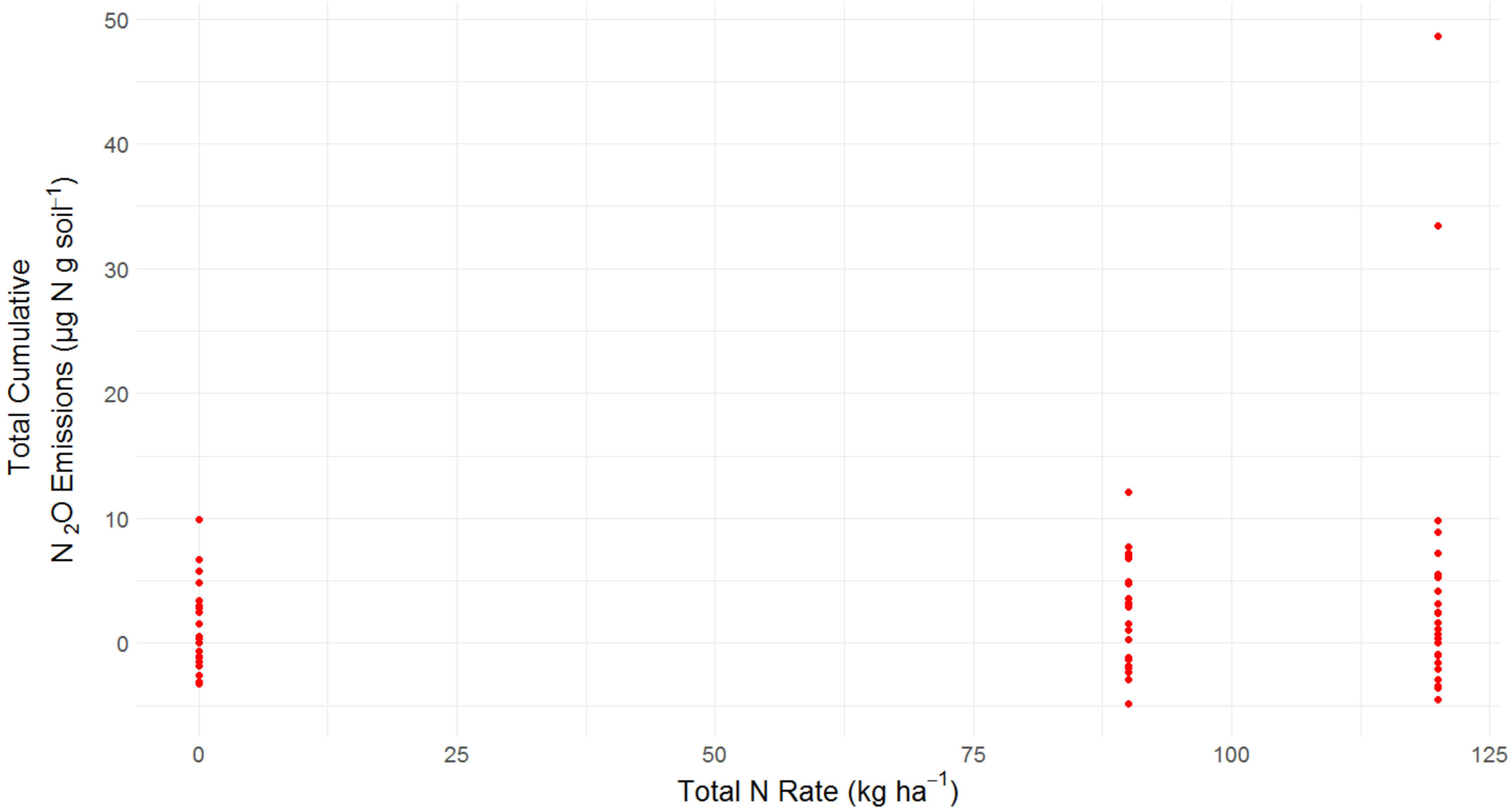

Figure 3-3. Cumulative N_2O emissions during the entire incubation period as a function of total added N fertilizer in treatments receiving no fertigation. (n= 72).

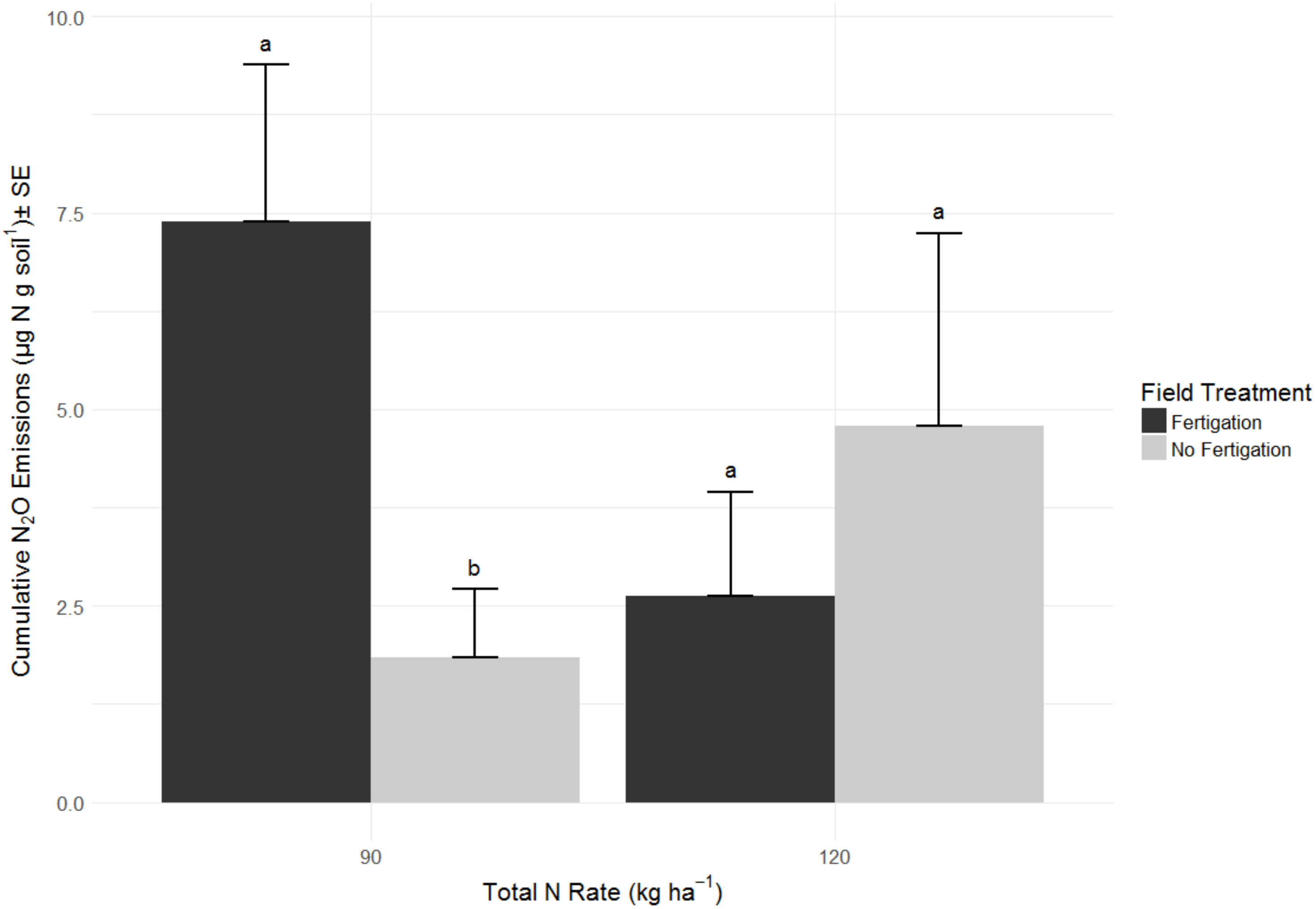

Figure 3-4. Cumulative N_2O emissions during the incubation period as a function of total rate of added N Fertilizer, through side banding at crop seeding (No Fertigation) and by both side banding plus through in-crop Fertigation (Fertigation) in early June. Comparisons were only made between treatments with equal total N rate. Same letters within each N Fertilizer rate indicate no significant differences based on Tukey's HSD.

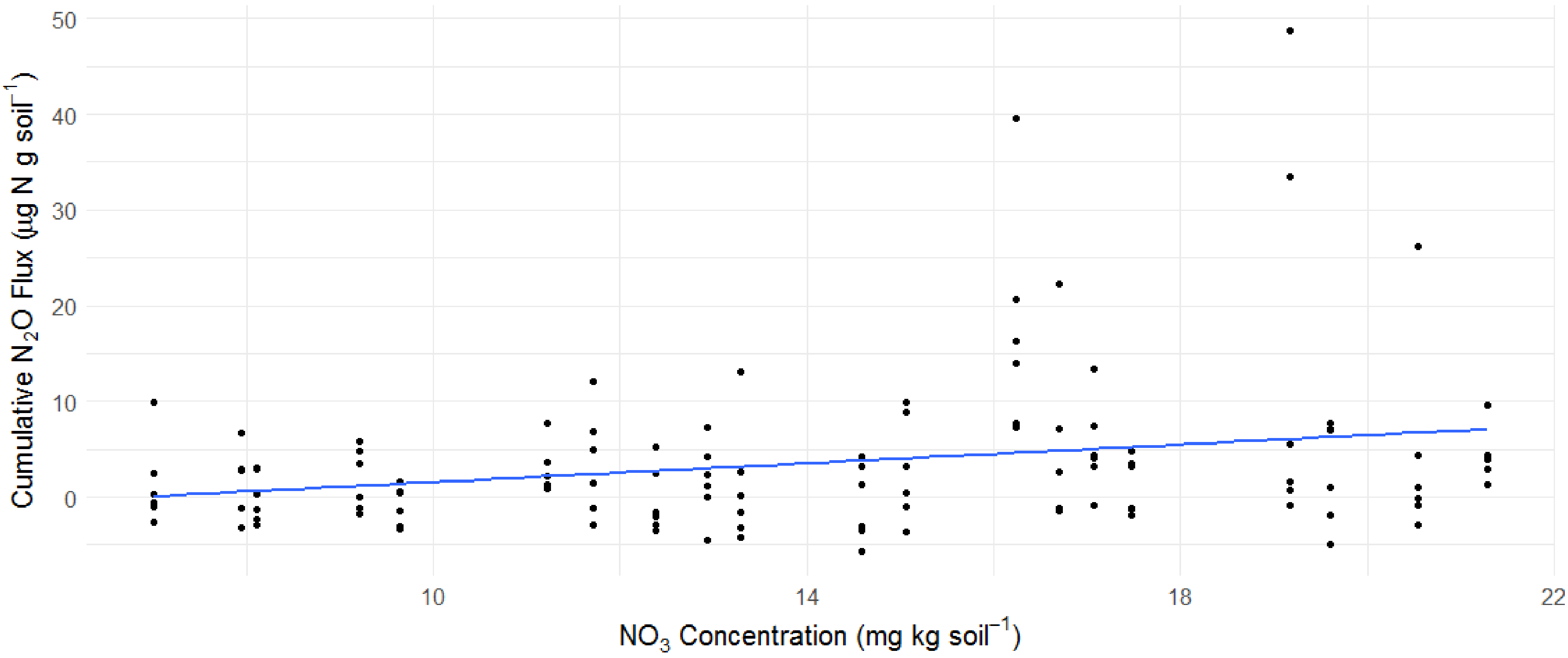

Figure 3-5. Cumulative nitrous oxide (N_2O) emissions as a function of soil nitrate concentrations as measured prior to the incubation period. This is the complete dataset encompassing six incubation units (microcosms) from each of the 20 field experimental plots (n= 120). There were two incubation units (as duplicates) for each of the three moisture treatments. The simple linear least squared regression equation corresponds to N_2O flux = -3.36 + 0.49NO_3-N; with p= 0.004 and coefficient of determination ($R^2 = 0.068$).

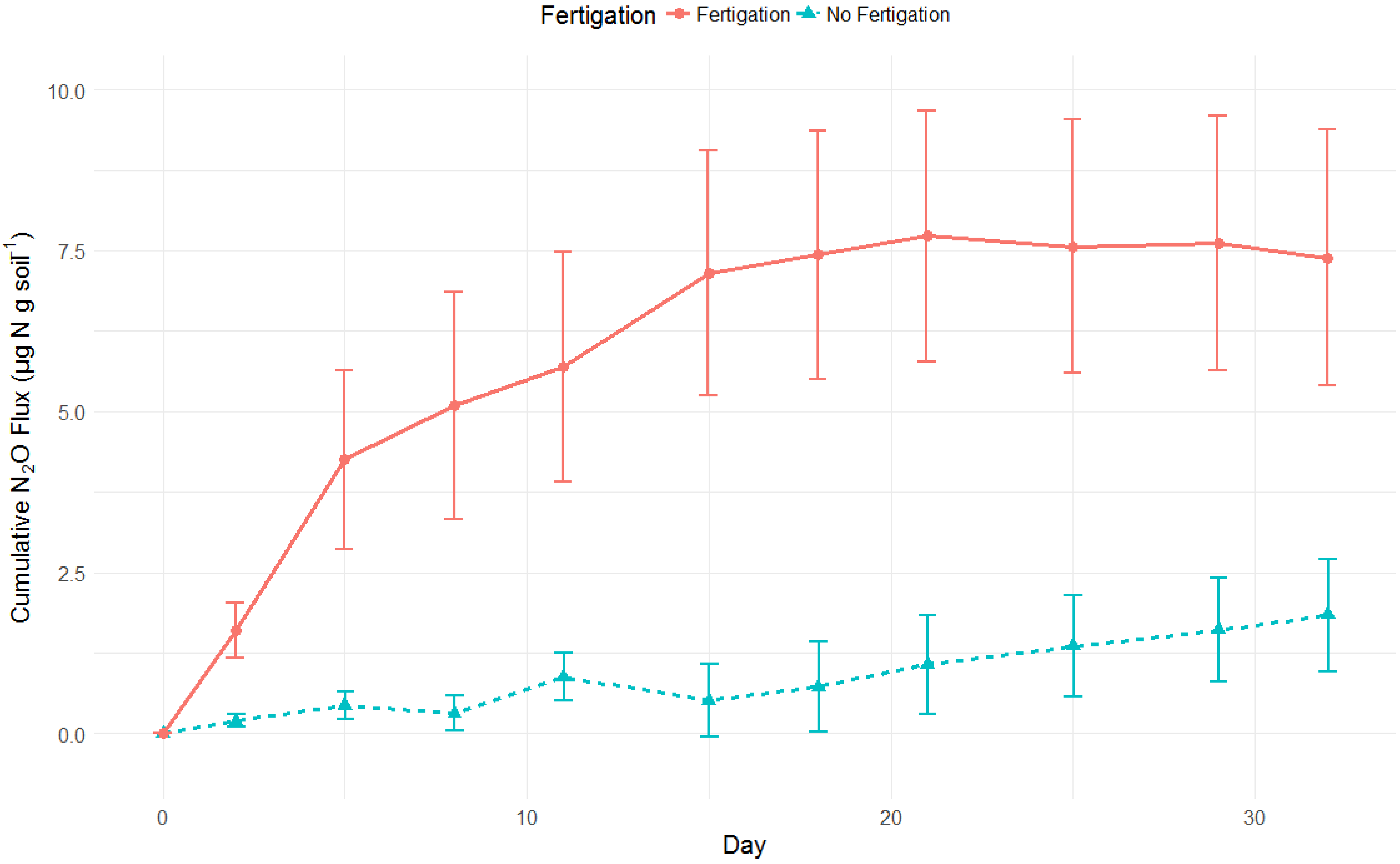

Figure 3-6. Cumulative nitrous oxide flux at a total N rate of 90 kg N ha^{-1} with and without fertigation during the incubation. Error bars are standard errors of the means.

4. General Conclusion

Field-measured N_2O production in wheat and canola displayed typical responses to additions of N fertilizer, with more N_2O produced under higher rates of fertilizer application; however, this trend was not observed under a controlled incubation of the same soils. These differences may be a result of the optimal conditions in the incubation differing from the field, and the fact that the soil for the incubation were taken in mid-June and likely did not capture high peak flux events that occurred early in the growing season after seeding applied fertilization, as seen in the field study. Our incubation study captured only the N_2O production from the soils at one specific time and was not influenced by the overall N rate of the field treatment but rather the effects of the more recent fertigation application applied in early June.

The effects of fertigation were not seen in all of the rates we tested, nor in all of the years or crops of the field experiment. There was no effect of fertigation on canola in area- or yield-based N_2O emissions, and thus fertigation management is likely not an efficient N_2O management technique for this crop of high N demands and fast crop residue decomposition. Wheat however, responded positively to split applications of N at the 60 and 90 kg N ha^{-1} rate in yield-based N_2O emissions and at the 90 kg N ha^{-1} rate in area-based N_2O emissions, although only in the 2016 study year. Fertigation was effective at reducing N_2O production from this crop by decreasing the amount of N available in the soil early in the year when crop growth and uptake were low, and providing N to the plants later in the year when plant uptake was higher. The largest source of N_2O production in all crops and both years was the early, spring time fluxes which occurred soon after the application of N at crop seeding. We suggest that the driving factors of these spring peak fluxes in wheat are the availability of N substrates in the soil coupled with high soil moisture conditions which can be amplified by irrigation applications and consecutive high rainfall events. These results indicate that split N application to reduce early season N concentrations in the soil, in particular directly after seeding, can be effective at reducing early pulses of N_2O while maintaining similar crop yields. There are opportunities for additional research which examines not only the N_2O production during the growing season but also in the fall and winter. Differences caused by fertigation, particularly during spring thaw, may be detected if year-round monitoring is conducted.

The laboratory incubation of the wheat crop soils in 2016 showed contradictory results at the 90 kg N ha^{-1} rate; rather than a reduction in N_2O production under fertigation (60-30 split), we measured an increase. The highest concentration of soil nitrate was found in this 60-30 split treatment due to the recent addition of UAN via fertigation and, as stated above, this high N substrate availability became the driving factor in the rate of N_2O produced in soil. Overall, the cumulative production of N_2O was positively correlated to nitrate availability when observing all microcosms in the laboratory experiment. The effects of larger plant sinks in response to higher spring N fertilization could explain in part the differences we observed in N_2O production between the 90 and 120 kg N ha^{-1} treatments; larger plant canopies can lead to larger N sinks and less risk of N remaining in the soil which can be vulnerable to transformation into N_2O.

Accumulation of nitrate and likely associated N_2O production varied irrespective of the applied moisture regimes in our controlled laboratory study. The observed accumulation of nitrate indicates that conditions for nitrification were met, but none of the applied soil moisture regimes were high enough to induce major denitrification in our experiment. For future studies, higher soil moisture can be tested to replicate spring thaw coupled with high spring rainfalls over multiple days or to simulate irrigation application shortly followed by an unexpected major rainfall. Imposing these moisture conditions can reasonably represent spring field conditions in southern Alberta.

Overall, fertigation can be used to reduce the risk for N_2O production in wheat at intermediate rates by managing N substrate availability in soils; however, proper irrigation management, in particular directly during and after additions of N through fertigation, need to be prioritized in order to reduce any high soil moisture that can be conducive to denitrification and high N_2O production.

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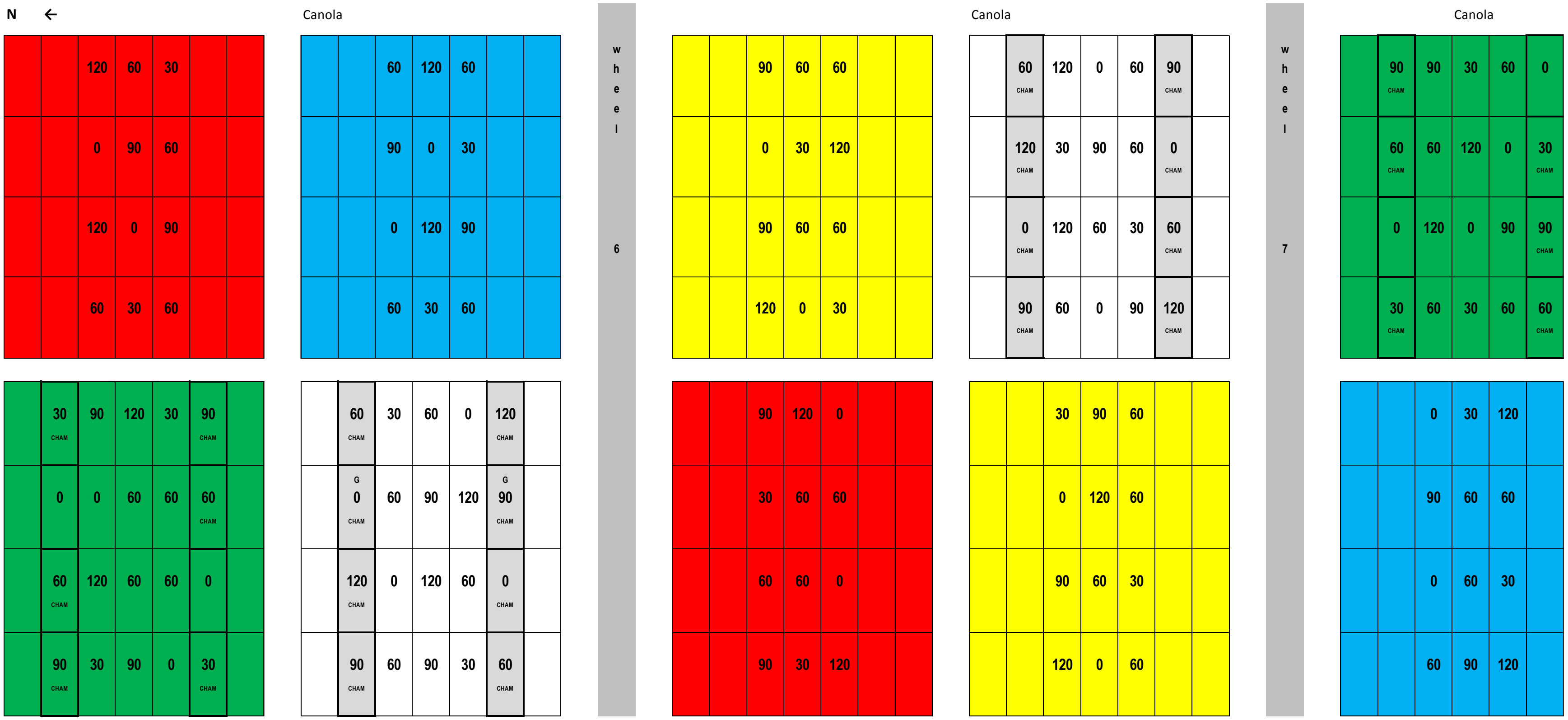
Appendix A

A complete list of all the treatments from the larger fertigation experiment at Lethbridge is listed below. In addition to the treatments described in the Materials and Methods section (Chapter 2), the field trial also tested the effects of applying 30 kg N ha^{-1} at seeding with no fertigation, all N rates at seeding plus fertigation at 2 additional crop growth stages (flag leaf for wheat and bolting for canola, or anthesis for wheat and flowering for canola), all N rates at seeding plus all three fertigation timings. This yielded a total of 5 fertigation regimes including the no fertigation and tillering or 5-leaf stage timings. Fertigation rates were always 30 kg N ha^{-1}, therefore, the total amount of N fertilizer added for this larger experiment ranged from 0 kg N ha^{-1} (no fertigation) up to 120 kg N ha^{-1} with 3 fertigation applications for a total of 210 kg N ha^{-1}. Additionally, the effect of using Environmentally Smart Nitrogen (ESN) was tested by applying 60 kg N ha^{-1} at seeding coupled with the 5 fertigation timings. The layout of the fertigation and seedling- applied treatments in the canola and wheat fields are included in the plot plans below. The color of the block indicates the different fertigation timings: white- no fertigation, green- tillering/ 5-leaf, blue- flag leaf/bolting, yellow- anthesis/flowering, and red- all timings. Each of these blocks includes 28 individual plots which either acted as a buffer (no seedling applied fertilizer applied and not used for measurements) or had a specific amount of fertilizer added to each plot at seeding (kg N ha^{-1}) indicated by the numbers within the plots. The dimensions of each individual plot within the blocks is 7 m by 2.3 m making each block 28 m by 16.1 m. The spacing between blocks was 11.5 m. The plots labelled with “CHAM” indicate the location of the chambers used in this study.

Fertigation Treatment	Side-banded N Rate at Seeding kg N ha^{-1}	Total N Rate kg N ha^{-1}
No Fertigation	0	0
	30	30
	60	60
	90	90
	120	120
	60 (ESN)	60
Tillering (wheat)/ 5-6 leaf (canola)	0	30
	30	60
	60	90
	90	120
	120	150
	60 (ESN)	90
Flag leaf (wheat)/ bolting (canola)	0	30
	30	60
	60	90
	90	120
	120	150
	60 (ESN)	90
Anthesis (wheat)/ flowering (canola)	0	30
	30	60
	60	90
	90	120
	120	150
	60 (ESN)	90
All three fertigation stages	0	90
	30	120
	60	150
	90	180
	120	210
	60 (ESN)	150

N ←



		120	60	30		
		0	90	60		
		120	0	90		
		60	30	60		

Canola

		60	120	60		
		90	0	30		
		0	120	90		
		60	30	60		

wheel 6

		90	60	60		
		0	30	120		
		90	60	60		
		120	0	30		

Canola

	60 CHAM	120	0	60	90 CHAM	
	120 CHAM	30	90	60	0 CHAM	
	0 CHAM	120	60	30	60 CHAM	
	90 CHAM	60	0	90	120 CHAM	

wheel 7

Canola

	90 CHAM	90	30	60	0
	60 CHAM	60	120	0	30 CHAM
	0	120	0	90	90 CHAM
	30 CHAM	60	30	60	60 CHAM

	30 CHAM	90	120	30	90 CHAM	
	0	0	60	60	60 CHAM	
	60 CHAM	120	60	60	0	
	90 CHAM	30	90	0	30 CHAM	

	60 CHAM	30	60	0	120 CHAM	
	G 0 CHAM	60	90	120	G 90 CHAM	
	120 CHAM	0	120	60	0 CHAM	
	90 CHAM	60	90	30	60 CHAM	

		90	120	0		
		30	60	60		
		60	60	0		
		90	30	120		

		30	90	60		
		0	120	60		
		90	60	30		
		120	0	60		

		0	30	120	
		90	60	60	
		0	60	30	
		60	90	120	

		60	120	30		
		90	60	0		
		0	60	60		
		30	120	90		

		90	120	60		
		0	30	60		
		90	60	30		
		120	0	60		

		0	120	90		
		30	60	60		
		60	120	0		
		30	90	60		

	30 CHAM	30	60	120	0	
	90 CHAM	90	60	0	60 CHAM	
	0	60	0	120	90 CHAM	
	60 CHAM	60	90	30	30 CHAM	

	G 120 CHAM	120	90	60	G 90 CHAM	
	G 60 CHAM	0	30	60	G 0 CHAM	
	G 90 CHAM	60	60	90	G 120 CHAM	
	G 0 CHAM	120	30	0	G 60 CHAM	

	90 CHAM	0	60	90	30 CHAM	
	60 CHAM	30	120	60	0	
	30 CHAM	30	0	60	60 CHAM	
	0	90	120	60	90 CHAM	

	0 CHAM	60	60	120	60 CHAM	
	120 CHAM	30	0	90	90 CHAM	
	90 CHAM	30	60	0	0 CHAM	
	60 CHAM	120	90	60	120 CHAM	

		30	60	60		
		120	0	90		
		0	60	60		
		30	120	90		

		60	120	90		
		0	30	60		
		60	0	60		
		90	120	30		

		90	30	0		
		60	60	120		
		0	60	60		
		120	30	90		