Date Received
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PROJECT REPORT

Project overview

1. Project number: 2016045R - RES0035051 - Potato Growers of Alberta - PGA		
2. Project title: Effects of Nitrification Inhibitor and Biostimulant on reduction of Nitrous Oxide (N2O) emissions and increase of Nutrient Use Efficiency in Intensive Potato Crops in Alberta, Canada		
3. Abbreviations: Define ALL abbreviations used.		
4. Project start date: 2/1/2017 Finish Date: 12/31/2019		
5. Project completion date: 12/31/2019		
6. Report submission date: 01/07/2021		
7. Research team information		
a) Principal investigator: (Requires personal data sheet (refer to Section 14) only if Principal Investigator has changed since last report.)		
Name	**Institution**	**Expertise added**
Guillermo Hernandez Ramirez	Associate Professor, University of Alberta, Faculty of Agriculture, Life and Environmental Sciences	Soil science & greenhouse gases fluxes
b) Research team members (List names of all team members. For each new team member, *i.e.*, joined since the last report, include a personal data sheet [refer to Section 14]. Additional rows may be added if necessary.)		
Name	**Institution**	**Expertise added**
Dr. Shakila K. Thilakarathna	University of Alberta	Postdoctorate in Soil fertility & gasesous fluxes
Dr. Michele Konschuh	Department of Biological Sciences, University of Lethbridge	Irrigation specilist
Dr. Shelley A. Woods	Alberta Agriculture and Forestry, Lethbridge Research Centre	Irrigation management

Principal Investigator and Authorised Representative's Signatures

The Principal Investigator and an authorised representative from the Principal Investigator's organisation of employment must sign this form.

By signing as an authorised representative of the Principal Investigator's employing organisation and/or the research team member's(s') employing organisation(s), the undersigned hereby acknowledge submission of the information contained in this report to the funder(s).

Principal Investigator

Principal Investigator	
Name: **Guillermo Hernandez Ramirez**	**Title/Organisation:** **University of Alberta**
Signature: **SEE SEPARATE FILE**	**Date:** **4 January 2021**
Principal Investigator's Authorised Representative's Approval	
Name: **David Bressler**	**Title/Organisation:** **Associated Dean Research – Faculty of Agriculture, Life and Environmental Sciences University of Alberta**
Signature: **SEE SEPARATE FILE**	**Date:** **4 January 2021**

Financial Project Report

M - 10AUG2020-YT

UNIVERSITY OF ALBERTA

Research Services Office
222 Campus Tower, 8625 - 112 Street, Edmonton, AB T6G 2E1 Canada

Statement of Award & Expenditures

For the Period Ending December 31, 2019

Name of Grantee	Department		Project/Grant	
Hernandez Ramirez Guillermo - Principal Investigator	100400	ALES RR General	Start Date:	End Date:
University Project/Grant Number	Project/Grant Description		Feburary 1, 2017	December 31, 2019
RES0035051	MULTI/2 PGA 2016C045R Hernande			

	Reporting Period Feburary 1, 2017 December 31, 2019
OPENING BALANCE	**0.00**
AWARD	
Direct Costs	**177,000.00**
Indirect Costs	**0.00**
Total funds available	**177,000.00**
EXPENDITURE	
Salaries & Benefits	
Undergrad Stu Salary & Benefit	0.00
Grad Student Salary & Benefits	0.00
Graduate Student Salaries	0.00
Graduate Student Benefits	0.00
Postdoctoral Salary & Benefits	0.00
Postdoctoral Fellows Salaries	0.00
Postdoctoral Fellows Benefits	0.00
Other Sal & Adj (all benefits)	0.00
Other Salaries	81,837.82
Other Benefits	6,087.86
Professional & Technical Svcs	19,364.32
Equipment	22,724.37
Materials Supplies & Other Exp	35,722.53
Travel	11,263.10
Transfers Out	0.00
	0.00
Total Funds Expended	**177,000.00**
Indirect Cost Expenses 0%	**0.00**
Total Expenditures	**177,000.00**
PROJECT/GRANT BALANCE AS AT: December 31, 2019	**0.00**
Amount Received from Sponsor:	**177,000.00**

SIGNATURES

I hereby certify that the above statement is correct and that the expenditures shown were for the purpose for which the grant was made and disbursements conform to University policy and are in compliance with all terms and conditions imposed by the sponsoring agency.

Project Manager - Role: Hernandez Ramirez Guillermo - Principal Investigator

12 Aug. 2020

Date

I certify that the expenditures summarized above were incurred and paid wholly on behalf of the grantee, and that the vouchers are available for monitoring purposes.

Michael Walesiak
Associate Director-Finance
Research Services Office

Business Officer, Research Services Office

August 12, 2020

Date

Activity Project Report

Potato productivity and nitrous oxide emissions as a function of nitrogen fertilization options

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Highlights

N_2O emissions from furrow positions were typically greater than from potato hills

Admixing the inhibitor DMPSA with N fertilizers decreased N_2O fluxes and increased yield

Polymer-coated urea also increased potato harvest, but did not reduce the N_2O fluxes

Fertilizer options did not influence the nitrogen use-efficiency or harvest indexes

Potato petiole nitrate concentrations were closely linked with availability of soil N

Abstract

Improved nitrogen management options are needed in intensive agricultural systems to mitigate the risk for N_2O emissions while sustaining high yields. We assessed the effectiveness of a polymer-coated urea (Environmentally Smart N™, ESN), a new nitrification inhibitor 2,4-dimethylpyrazol succinic acid (DMPSA), a novel biostimulant (an existing bacterial and enzymatic combination), and their combinations with granular urea and ammonium sulfate nitrate (ASN) fertilizers to decrease nitrous oxide (N_2O) emissions and to improve potato (*Solanum tuberosum* L.) productivity under irrigation in Southern Alberta, Canada. We measured the emissions of N_2O from potato hills and furrows at two field sites throughout two growing seasons using the manual chamber method. Tuber yield and grade as well as N uptake were also quantified. Peak N_2O emissions as well as increased N concentrations in potato petiole and soils occurred shortly after N fertilizer applications. Although the effects were not always evident, the urea alone treatment generally exhibited the highest N_2O fluxes, whereas the DMPSA inhibitor admixed with either urea or ASN resulted in lower N_2O emissions. In one of the growing seasons at the Brooks site, adding DMPSA reduced the N_2O emissions from urea-amended fields by 57 %. At the Lethbridge site, the N_2O emissions from furrow positions were greater than from hills by 3.2 times in 2017 and 1.7 times in 2018. Compared to the unfertilized controls, 36% higher potato marketable yields were obtained when applying either ASN treated with DMPSA or ESN fertilization options in one of the four experimental site-years (33 versus 45 Mg ha^{-1}). The overall average of growing-season N_2O emission factor was 0.056 %, after accounting for considerable background emissions from unfertilized controls. Results showed that N application strategies utilizing DMPSA admixed with either urea or ASN can maintain high potato yields while reducing N_2O emissions relative to soils receiving these fertilizers without this additive.

Keywords:

Potato, Nitrous oxide, Nitrogen fertilizer, Nitrification inhibitor, Irrigation

Introduction

Global food security and climate change are two crucial challenges inherently associated with land management options. Agricultural lands that receive intensive nitrogen fertilization are important sources of food commodities and also detrimental greenhouse gases such as the potent nitrous oxide (N_2O) (Lin et al., 2017; Thilakarathna et al., 2021; Chai et al., 2020). In fact, the outcomes of N_2O emissions and crop productivity can trade off with each other (Thilakarathna et al., 2021) or even increase concurrently (Chai et al., 2020) under the driving influence of N fertilization choices. Furthermore, in irrigated fertilized croplands (Chai et al., 2020), soils can experience high availabilities of N and moisture simultaneously, which can exacerbate production of N_2O from both exogenous and native N pools (Roman-Perez and Hernandez-Ramirez, 2021). Concerns about N_2O as a greenhouse gas exist because N_2O is 300 times more powerful than CO_2 on mass basis (Daly and Hernandez-Ramirez, 2020). As a highly stable gas, N_2O can persist in the atmosphere for 120 years and depletes the stratospheric ozone layer through catalyzed reactions (Ravishankara et al., 2009). In addition to N_2O emissions, other losses of applied fertilizer-N to the environment can involve dinitrogen from complete denitrification, ammonia (NH_3) volatilization, eutrophication in surface water, and groundwater contamination from nitrate leaching (Hernandez-Ramirez et al., 2011; Lin et al., 2017; Liang et al., 2019).

As a high productivity crop, potato (*Solanum tuberosum* L.) requires significant inputs of N and water to optimize yield, maintain tuber quality, and tolerate diseases (Ghosh et al., 2019). Within Canada, one of the largest concentrations of potato cropping is located in southern Alberta, with a planting area of 22,424 ha (Agricultural Statistics Alberta, 2018). Generally, the application rates of N fertilizer for irrigated potato cropping in the Canadian Prairies are greater than 200 kg N ha^{-1} (Gao et al., 2013); hence, high-input intensity potato cropping can likely be characterized as hot spot for greenhouse gas (GHG) emissions and potentially reduced nutrient use efficiency (NUE). This net outcome from potato production could become detrimental from agronomic, economic, and environmental perspectives. Reduced NUE increases the cost of production and decreases yield per unit area, creating challenges in meeting the global demand for food production (Thilakarathna et al., 2021).

Enhanced crop productivity and a reduced environmental footprint are closely related to efficient N cycling and transformations that result from well-timed nutrient availability in close synchrony with plant requirements (Venterea et al., 2012). Improving N management in intensified cropping systems can create opportunities to simultaneously achieve both sustained productivity and reduced environmental impacts. Such management improvements can emerge through the split application of N fertilizers (Gao et al., 2017; Souza et al., 2020), addition of controlled-release N fertilizers (Akiyama et al., 2010; Thilakarathna et al., 2021), nitrification inhibitors admixed with N fertilizers (Lin et al., 2017; Thilakarathna et al., 2021), and novel biostimulants of the soil N cycling that can combine beneficial bacterial and enzymatic actions (Calvo et al., 2013; Calvo et al., 2014; Souza et al., 2019). A microbial biostimulant containing beneficial free-living N-fixing and mineralizing microbes could potentially increase the amount and availability of N for crops while stimulating root growth and increased nutrient uptake (Souza et al., 2019; Zarzecka et al., 2019).

Compared to the common use of urea fertilizer in agriculture (Guenette et al., 2019), ammonium sulfate nitrate (ASN) could potentially deliver higher N availability per added N unit to crops as an alternative fertilizer. Furthermore, treating urea or ammonium-based fertilizers with a nitrification inhibitor, such as 2,4-dimethylpyrazol succinic acid (DMPSA), has the capacity to retain available N in ammonium form (Guardia et al., 2017; Thilakarathna and Hernandez-Ramirez, 2021). After evaluating urea treated with the inhibitor 2,4-dimethylpyrazol phosphate in a potato crop in Minnesota, Souza et al. (2019) reported that N_2O emissions decreased by half compared with urea alone. To the best of our knowledge, there is a paucity of studies examining the effects of the newly-formulated inhibitor DMPSA on potato production. It is unclear how beneficial implementing DMPSA additive would be on both potato yield and N_2O emissions. Our study endeavors to address this knowledge gap.

Controlled-release N fertilizers may also prevent N losses and improve timely N availability in cropping systems (Li et al., 2012; Li et al., 2016; Thilakarathna et al., 2021; Ziadi et al., 2011). A common controlled-release fertilizer is the polymer-coated urea (PCU) known as Environmentally Smart N™ (ESN). To date, only a few studies have determined the effectiveness of ESN on N_2O emissions in potato production fields, and these existing studies reported inconsistent results (Motavalli et al., 2008; Perron et al., 2019; Ziadi et al., 2011). Hyatt et al. (2010) reported that PCU reduced N_2O emissions or had no effect in irrigated potato in Minnesota, while Zebarth et al. (2012) found no significant effect of PCU on N_2O emissions from rain-fed potato production on a medium-textured soil in Eastern Canada. These inconsistent, scarce reports point to the need for further research to determine the effectiveness of ESN as available results were highly influenced by specific soil, weather, and management practices.

The N_2O emissions within potato fields are highly spatially variable because of the creation of hills and furrows during hilling operations (Burton et al., 2008; Gao et al., 2013). Burton et al. (2008) reported N_2O emissions from potato hills to be greater than furrows during the first two years of an N banded field experiment conducted in Orthic Humo Ferric Podzols in

Eastern Canada. By contrast, both Ruser et al. (2006) in Southern Germany and Smith et al. (1998) in the United Kingdom observed higher N_2O emissions from furrows relative to potato hills. These conflicting reports highlight the need for better understanding of spatial and temporal patterns of N_2O fluxes from hills and furrows within potato fields across a range of environments. This investigation needs to be conducted along with examination of N availability in soils during the growing season in order to identify, develop and improve mitigation options.

The objectives of this study were (i) to determine the N_2O emission reduction potential of several N fertilization options in irrigated potato production, (ii) assess the temporal fluctuations over the cropping season and spatial variability of N_2O emissions in hills and furrows within the potato management zone, and (iii) to evaluate the effects of the several N fertilizer formulations on potato productivity and N utilization.

Materials and methods

Site Description

Field experiments were conducted during the growing seasons of 2017 and 2018 near Lethbridge (49° 41' 12.12" N, 112° 44' 41.64" W) and Brooks (50° 32' 60" N, 111° 50' 60" W), Alberta, Canada. Soil classifications are Dark Brown Chernozem for Lethbridge and Brown Chernozem for Brooks. Initial soil properties of the 0-15 cm depth increment were pH of 7.6 and 7.8 (1:5 soil: water), electric conductivity of 0.50 and 0.62 dS m^{-1}, total organic carbon content of 14±0.7 and 10±0.9 g C kg^{-1}, and a total N content of 1.4±0.1 and 1.1±0.1 g N kg^{-1} for Lethbridge and Brooks, respectively. Organic C and total N were measured via dry combustion method (Li et al., 2018). Both sites were characterized with a sandy clay loam soil texture as measured with the hydrometer method.

Experimental Design

The experiments used a randomized complete block design with four replicates. Experimental plots had dimensions of 3.6 m wide and 9 m long for a plot area of 32 m^2. Blocks were separated from each other by a 4 m wide buffer zone.

Eleven experimental treatments were applied consistently within each of the four site-years in the study. The assessed treatments were: (1) control (no fertilizer or additives), (2) biostimulant (Eurochem Group, Mannheim, Germany) (no N fertilizer added), (3) granular urea (46% N), (4) urea + DMPSA (Eurochem Group, Germany), (5) urea + biostimulant, (6) urea + DMPSA + biostimulant, (7) ammonium sulfate nitrate (ASN) (26% N), (8) ASN + DMPSA, (9) ASN + biostimulant, (10) ASN + DMPSA + biostimulant, and (11) ESN 44% N (polymer coated urea) (Nutrien, Saskatoon, SK, Canada). The nitrification inhibitor DMPSA was admixed with urea and ASN a rate of 0.8 kg a.i. ha^{-1}. The biostimulant was surface sprayed at a rate of 2.5 L ha^{-1} and incorporated at the time of hilling.

All N fertilizer treatments were applied at the uniform rate of 200 kg N ha^{-1} yr^{-1}, which was 80% of the commercially-recommended rate based on soil sampling and N analyses. For all N fertilizer treatments with the sole exception of ESN, split N fertilization was conducted with 65% of the N at pre-planting and 35% as post-planting N at hilling operation. In the only case of ESN, all N was applied at pre-planting. Pre-planting N additions were applied and incorporated mechanically with a Conserva-Pak. Subsequently, a Russet Burbank potato cultivar was planted at a soil depth of 15 cm and four rows per experimental plot, with a 2-row Checci tuber-unit planter at Brooks and a 4 row cup planter at Lethbridge. Seed potato were planted at a rate of 1 Mg ha^{-1} with 0.9 m row spacing and 0.3 m seed spacing. Hilling operation was conducted with a mechanical power hiller. This hilling operation aims at preventing tuber greening as well as it facilitates weed control and subsequent potato harvesting. The fertilizer-N added at hilling was surface applied with a portable broadcasting device just prior to the mechanical hilling operation. Harvest was done with a one-row Grimme harvester. In both experimental years, tuber grading was done by weighing and separating tubers into the following mass categories of <113, 113-170, 170-284 and >284 g. All tubers >113 g were considered as marketable tubers. Water content in the potato tubers was measured by oven-drying samples.

Other fertilizers such as phosphorus (triple super phosphate), potassium, and sulphur were broadcasted and incorporated prior to planting at Lethbridge at a rate of 136 kg P ha^{-1}, 136 kg K ha^{-1}, and 18 kg S ha^{-1}, respectively. The Brooks site received broadcasted and incorporated phosphorus in the form of monoammonium phosphate (MAP).

Irrigation water was added to both study sites. This represents a common agronomic management as commercial potato crops in Southern Alberta can be grown only under irrigation. All experimental fields were irrigated via overhead low-pressure sprinklers. Irrigation water was sourced from the St. Mary's River Irrigation District near Lethbridge, and from the Eastern Irrigation District near Brooks. The frequency and amount of irrigation were based on evapotranspiration replacement and estimated by the Alberta irrigation management model (AIMM) − an evapotranspiration-based method of determining irrigation requirements.

Weeds, insects, and fungal diseases in the potato fields were controlled using recommended pesticides and rates.

In the first experimental year, the Lethbridge site received N fertilizer treatments on 8-9 May 2017, while fertilizer application at the Brooks site was on 23 May 2017. Planting took place on 10 and 26 May in 2017 at Lethbridge and Brooks, respectively. Post-planting N fertilizer addition and hilling operation were conducted on 31 May 2017 at Lethbridge and 8

June 2017 at Brooks. At the end of the growing season, potatoes were harvested on 27 and 29 Sept. 2017 at Lethbridge and Brooks, respectively.

For the second study year 2018, experimental plots were moved to a new adjacent location within a distance of 200 m. All fertilizer treatments and agronomic practices were conducted in 2018 in the same manner as in 2017. Pre-planting N fertilizers were applied on 8 and 15 May 2018 at Brooks and Lethbridge, respectively. Planting occurred on 17 and 25 May 2018 at Lethbridge and Brooks, respectively. Post-planting fertilization and hilling operation were conducted on 4 and 7 June 2018 at Lethbridge and Brooks, respectively. Potato was harvested mechanically on 26 and 28 Sept. 2018 at Lethbridge and Brooks, respectively.

Soil moisture and temperature was recorded every 30 minutes using dataloggers and sensors (5TM, Meter, Pullman, WA) at the soil depths of 10 and 22.5 cm in hills, and 7.5 and 22.5 cm in the furrow.

Nitrous oxide flux measurements

The N_2O fluxes at the soil surface were measured using a manual nonsteady-state closed chamber methodology (Lin et al., 2017; Thilakarathna et al., 2021). To capture N_2O emissions in the hills and furrows of the potato fields, sets of chambers were installed separately at potato hill and furrow positions. Within an experimental plot, one chamber base was placed in the potato hill, and one chamber in the furrow position. Chamber bases in the hills were installed in the middle potato rows and at a 7 cm soil depth after planting. Chamber bases were removed prior to post-planting fertilization and hilling operation as well as for potato harvesting and reinstalled immediately in the same locations.

We used circular chamber bases with 10 cm in height and 20 cm in inner diameter. Circular detachable chamber lids with 10 cm in height were used to generate a headspace for gas sample collection. Three gas samples of 20 mL were collected through a rubber septum port fitted in the chamber lid with a syringe. Gas samples were withdrawn at 11, 22, and 33 minutes following chamber enclosure. The collected gas samples were immediately injected into a 12 mL pre-evacuated glass vial (Exetainer, Labco, UK). To estimate the gas concentrations at time zero (Time 0), ambient air samples from outside of the headspace at chamber height were collected at the start, middle, and end of the sampling period.

Flux measurements were conducted weekly. Depending on the weather (e.g., heavy rainfall events) and farming activities (e.g., hilling, post planting fertilization), gas sampling frequency was increased to twice per week. On dates of gas sample collection, flux measurements were conducted between 1030 and 1430 h. On every sampling date during the growing season, we collected gas samples from chambers located in both hills and furrows. Post-harvest fluxes were measured from each experimental plot using one chamber per plot as there were no hills and furrows after potato harvesting.

In 2017, fluxes were quantified in all experimental treatments. Based on the flux results quantified in 2017, flux measurements in 2018 specifically focused in six selected experimental treatments − i.e., treatments 1, 3, 4, 7, 8, and 11 as listed above.

The N_2O concentration of gas samples were analyzed using an electron capture detector in a Varian 3800 gas chromatograph system (Varian Inc., Walnut Creek, CA) (Lin et al., 2017). The minimum analytical detectable concentrations was 10 ppb precision for N_2O (n= 30) (Lin and Hernandez-Ramirez, 2020). To further ensure quality control, the gas chromatography in each analytical run was calibrated with certified reference gases of N_2O with concentrations ranging from 0.25 to 4.84 $\mu L\ L^{-1}$ and N_2 as balance (Praxair Specialty Gases, Edmonton, AB). Fluxes were determined using the change of N_2O concentration over the 33-minute chamber enclosure period (with four gas sample collection times of 0, 11, 22, and 33 min) (Lin et al., 2017; Chai et al., 2020; Thilakarathna et al., 2021). Fluxes were estimated via fitting linear or quadratic relationships basis of the highest coefficient of determination (R^2) and the lowest p-value. An alpha critical value of 0.20 was used to determine the non-significant fluxes, which were retained in the data set. The N_2O flux was calculated as:

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

The N_2O flux is the flux rate of N_2O (μmol m^{-2} min^{-1}), S is the slope of the line from either the simple linear regression or the first-order derivative at Time 0 from the quadratic curve (μL L^{-1} min^{-1}), P is the gas pressure (Pa), V is the volume of the chamber (L), A is the surface area of the chamber (m^2), R is the gas constant (Pa μL K^{-1} $μmol^{-1}$), and T is the temperature of the gas (K) (Thilakarathna et al., 2021).

The cumulative N_2O emissions for each growing season were calculated using simple linear interpolations of the time series of flux measurements. The integration of fluxes from hills and furrows into a flux representative of the whole management zone in potato was done by averaging the N_2O emissions from hills and furrows. This accounts for 50% of the potato fields being represented by flux measurements taken in the potato hills and with the other 50% of the field area corresponding to furrows.

Area-based emission factors (EF_{area}) are the percentages of N applied as fertilizer emitted as N_2O-N and calculated accounting for baseline N_2O-N emissions from the control plot within each experimental block in every site-year as follows:

$$EF_{area} = \frac{(N_2O\ treatment - N_2O\ control)}{fertilizer\ applied} * 100 \quad [2]$$

For comparison purposes, N_2O EF were also estimated as a function of total water addition of rainfall and irrigation based on the exponential equation postulated by Rochette et al. (2018) and Liang et al. (2020) as follows: N_2O EF % = $e^{(0.00558 \times H2O - 7.701)} \times 100$.

Soil N measurements

Composite baseline soil samples (four cores per block replicate) were collected from the depth increments of 0-15, 15-30, 30-60, and 60-90 cm prior to the beginning of the growing season. Baseline soil samples were analyzed for ammonium and nitrate concentrations. These baseline N results were taking into consideration when establishing the N fertilization rate.

To capture N transformations and changes in ammonium and nitrate concentrations during the growing seasons, soil samples were repeatedly collected from the 0 to 15 cm depth increments with a push probe (2.5 cm inner diameter). From each plot, composite samples (n= 3) were collected separately from potato hills and furrows.

All soil samples were air-dried, ground, and passed through a 2 mm sieve. A 5 g subsample was extracted with 50 mL of 2 M KCl (1:10 soil:extractant) with 30 minutes of horizontal reciprocal shaking. The concentrations of NO_3–N and NH_4–N were measured colorimetrically on a SmartChem discrete wet chemistry analyzer (Westco Scientific Instruments Inc., Brookfield, CT).

Plant N measurements

Similar to soil samples, potato petiole samples were also collected and analyzed for nitrate concentration to examine the plant N status throughout the growing season. In 2017, field sample collections of both soils and petioles from each experimental plot were performed on 12 July, 3 and 17 of Aug. at Brooks, and on 28 June, 17 July and 8 Aug. at Lethbridge. In 2018, soils and petioles were collected on 6 and 24 July and 15 Aug at Brooks, and on 26 June, 17 July and 7 Aug. at Lethbridge.

Petioles were collected from the fourth leaf from the growing tip of the potato plants. During field collection of petiole samples, the corresponding leaflets were removed. Petiole tissue samples were kept in a cooler on ice until delivered to the analytical laboratory within 24 h of sample collection. Petioles were oven dried at 55°C to determine the dry matter content. Samples were ground with a Wiley grinding mill, and N concentrations in the petiole were measured using a nitrate-ion specific electrode (Vitosh and Silva, 1994). Results were expressed as mg nitrate-N per kg dry matter (DM) petiole tissue.

Composite samples of aboveground whole plants were collected from each experimental plot immediately prior to harvest, and subsequently oven dried, weighted and ground. A subsample of plant material was analyzed by total Kjeldahl N digestion-distillation-titration method. Eight marketable potato tubers were randomly collected after grading, hand-washed and diced using a Hobbart commercial mixer with a dicing attachment. A subsample of diced tubers was freeze dried and ground before conducting total N analyses. N uptake in potato tubers and canopy were determined as the product using DM and N content data.

Yield-based emission factors (EF_{yield}), which is growing-season N_2O emission per kg of potato tuber, were estimated (Chai et al., 2020; Thilakarathna et al., 2021). The partitioning of DM and N between tubers and aboveground canopy was calculated as harvest index (HI) and N harvest index (NHI), respectively (Geremew et al., 2007; Hernandez-Ramirez et al., 2011). Since the parameters of marketable yield can vary between geographic regions worldwide, NUE, HI, NHI and EF_{yield} calculations were done based on the total tuber yield (Milroy et al., 2019). The yield-based emission factor (EF_{yield}), fertilizer NUE, HI, and NHI were determined as:

$$EF_{yield} = \frac{N_2O\ treatment}{Tuber\ yield} \quad [3]$$

$$Fertilizer\ NUE\ = \frac{Tuber\ yield_{treatment} - Tuber\ yield_{control}}{N\ rate} * 100 \quad [4]$$

$$HI\ = \frac{Tuber\ yield\ DM}{Total\ biomass\ DM} \quad [5]$$

$$NHI\ = \frac{Tuber\ N}{Total\ biomass\ N} \quad [6]$$

Statistical analyses

All the data were tested for the assumptions of normality and homoscedasticity using the Shapiro-Wilk and Bartlett tests, respectively. Data was Box-Cox transformed when needed to meet the assumptions. The effects of the fertilizer treatment, hill vs. furrow positions and their interaction on N_2O emissions and soil available N was assessed using two-way analysis of variance (ANOVA). The treatment effects on cumulative N_2O emissions, potato tuber productivity, and petiole nitrate concentrations were tested using one-way ANOVA. Post-hoc tests were conducted with Tukey's Honest Significant Difference (HSD). Simple regressions were performed to assess the strength of relationships between soil available N and petiole N. All statistical analyses were conducted with SigmaStat (4.0) software at an alpha critical level of 0.05.

Results

Heat and water inputs over the growing seasons

The thirty-year normal mean air temperature for May to September (growing season) at Lethbridge and Brooks are 14.9 ^{o}C and 15.2 ^{o}C, respectively. During the growing season of May-September 2017 and 2018, the average monthly air temperature in both study sites were slightly greater than the thirty-year normal monthly averages (Fig. 1).

Lethbridge and Brooks have a thirty-year normal total growing season (May to September) precipitations of 252 mm and 211 mm, respectively. The distribution of precipitation differed between the years 2017 and 2018. In 2017, May and June received high rainfall at both sites whereas throughout July-September the sites experienced lower precipitation (Fig. 1). Moreover, during the growing season 2018, overall precipitation was lower than normal.

The Lethbridge site received 368 mm of irrigation water in 2017 and 379 mm in 2018. The amount of irrigation for the Brooks site were 366 mm in 2017 and 322 mm in 2018. It is noted that the Lethbridge site received more irrigation and total water input (i.e., rainfall + irrigation) in comparison to the Brooks (Table 1).

Based on heat units available for potato growth within the two growing seasons during the study, potato physiological days (P-Days) at Lethbridge in 2017 and 2018 were 911.9 and 917.4, respectively. The Brooks site received 895.2 of P-Days in 2017 and 859.4 in 2018.

Daily and growing-season N_2O emissions in response to N additions

In both years (2017 and 2018) and experimental sites (Lethbridge and Brooks), episodes of N_2O emissions occurred after pre-planting fertilizer and post-planting fertilizer applications (Fig. 2E, Fig. 2F, Fig. 3E, and Fig. 3F). The magnitude of the N_2O emission peaks in response to the pre-planting fertilizer application was greater than after the post-planting fertilizer addition. Furthermore, the N_2O emission peaks following the post-planting N addition were more evident in the furrow positions than in the potato hills. The urea alone treatment displayed the highest fluxes in the hill position at both experimental sites. At Lethbridge, on 24 May 2018, the N_2O flux from the urea alone treatment in the hill position was significantly greater than the control, urea + DMPSA, ASN + DMPSA, and ESN treatments ($P< 0.011$) (Fig. 2E and Fig. 2F). On 7 June 2018, at Lethbridge, we also observed significantly higher emissions from the urea alone treatment over the control treatment by 6-fold ($P< 0.031$) (Fig. 2E and 2F). Likewise, the urea alone treatment exhibited an elevated N_2O flux at Brooks on 20 June 2018 that was significantly greater than the control, urea + DMPSA, ASN, and ASN + DMPSA treatments ($P< 0.007$) (Fig. 3E and Fig. 3F). Even though no statistically significant difference was detected, N_2O emissions from the urea + biostimulant treatment were noticeably elevated on 6 June 2017 in both the hill and furrow positions at Lethbridge.

The application of urea largely increased the growing-season cumulative N_2O emissions regardless of the study site (Fig. 4). In the hill positions at the Lethbridge site, the mean cumulative N_2O emissions from the urea treatment (289 g N_2O-N ha^{-1}) were significantly greater than the control treatment (101 g N_2O-N ha^{-1}) ($P < 0.015$). In 2018, the highest cumulative N_2O emissions at Brooks were observed in the urea treatment (352 g N_2O-N ha^{-1}), which was significantly greater than all the other N treatments in the hill position ($P < 0.001$). In the furrow position, N_2O emissions from ASN (186 g N_2O-N ha^{-1}) were 3.8 times greater than the control treatment (46 g N_2O-N ha^{-1}) ($P < 0.032$) (Fig. 3). It is noticeable that significant higher N_2O emissions were observed from the furrow position in comparison to the hill position at Lethbridge, reporting 3.2 times greater emissions in 2017 and 1.7 times greater in 2018 (Fig. 4). There were no significant differences between the hill or furrow positions at Brooks.

The average growing-season cumulative emissions across all treatments in the Lethbridge site was 578 g N_2O ha^{-1} in 2017 and 256 g N_2O ha^{-1} in 2018. The mean cumulative emissions for the Brooks site was 94 g N_2O ha^{-1} in 2017 and 165 g N_2O ha^{-1} in 2018. The mean cumulative emissions for all treatments were significantly different between the two experimental years at both sites. In 2017 at the Lethbridge site, the average growing-season cumulative emission of all treatments were significantly higher than in 2018 ($P < 0.001$), whereas opposite results were observed for the Brooks site (2017 < 2018) ($P < 0.001$). When N_2O emissions in both experimental years were averaged across experimental sites, the mean cumulative N_2O emissions at Lethbridge were higher than at Brooks ($P < 0.001$).

Area- and yield-based N_2O emission factors

Across N fertilizers, experimental years and sites, the area-based emission factors (EF_{area}) were consistent and low, with an overall average of 0.056 % and with treatment means ranging between -0.079 and 0.100 % kg N_2O-N kg^{-1} N fertilizer (Table 2). During the experimental year 2017, all N fertilizer treatments in the Lethbridge site exhibited a high EF_{yield}, which differed significantly across experimental years and sites ($P< 0.05$) (Table 2).

Nitrogen dynamics in soil solution and plant tissues

Available soil N (NH_4 + NO_3) became high with the pre-planting fertilization and decreased over the growing season (Fig. 2C and Fig. 3C). Even though higher N_2O fluxes were observed at Lethbridge furrow positions than hill positions, no significant differences were found in available N between hill and furrow positions. Comparing the two study sites, overall available N concentrations trended higher at Lethbridge than at Brooks.

Similar to available soil N, petiole nitrate concentrations for all treatments gradually declined over the growing season (Fig. 2D and Fig. 3D). As expected, the control treatment had the lowest petiole nitrate concentrations in all four site-years. At Brooks-2018, petiole nitrate concentrations were significantly higher in the urea, ASN, and ESN treatments than the unamended control ($P< 0.001$) (Fig. 3D). Likewise, at Brooks-2017, several fertilized treatments had significantly greater petiole nitrate than the control and biostimulant alone treatments in the first (i.e., urea, urea + biostimulant, urea + DMPSA + biostimulant, ASN, and ASN + DMPSA) and second (i.e., urea + DMPSA, urea + biostimulant, ASN, and ESN) sample collections over the growing season ($P< 0.001$). Petiole nitrate concentrations in 2018 at Lethbridge were overall significantly greater than in 2017 ($P< 0.001$) (Fig. 2D). Overall, petiole nitrate concentrations at Lethbridge were greater than at Brooks. At Brooks, the nitrate concentrations in potato petiole at the first tissue sample collections (early July) in 2017 and 2018 were similar; however, the N decline between second and third tissue sample collections was more pronounced in 2018 than in 2017 ($P< 0.001$). At the third petiole sample collection date within the two growing seasons, the range of nitrate concentrations showed a significant difference between 2017 (3000-8000 mg N kg^{-1}) and 2018 (250-3000 mg N kg^{-1}).

Since soil available N and petiole N both declined over the growing season (Fig. 2 and Fig. 3), their inter-relationship was evaluated. Significant linear regressions were found between soil available N (ammonium plus nitrate) and petiole nitrate concentration for each of the four site-years in our study ($P< 0.001$) (Fig. 5).

Within each experimental site and year, total N contents (%) in tuber and canopy at potato maturity stage were not statistically different across N treatments (Table 3). At the Lethbridge site, N in both canopy and tuber were significantly different between experimental years (2017 vs. 2018) ($P< 0.001$), where tuber N concentration was lower and canopy N concentration was higher in 2018 than in 2017.

Potato productivity, NUE, N uptake, HI and NHI

In all experimental sites and years, both urea with DMPSA and ASN generated the highest total and marketable tuber yields while the control and biostimulant treatments resulted in the lowest (Table 4). The mean tuber mass of both ASN and ESN treatments (193 g) at the Lethbridge site in 2018 were significantly greater than the ASN + biostimulant (162 g). The N fertilizer sources did not significantly affect total yield, marketable yield, or specific gravity; except for the above noted differences in mean tuber mass in Lethbridge-2018 (Table 4).

Among year comparisons, potato productivity at both sites were numerically greater in 2018 than in 2017. Statistically significant differences in mean total yield and marketable yield at Brooks were observed between 2018 (57 Mg ha^{-1}, 38 Mg ha^{-1}) and 2017 (77 Mg ha^{-1}, 64 Mg ha-

^{1}), respectively ($P < 0.001$) (Table 4). When comparing the two experimental sites, the mean total yield in 2017 and marketable yield in 2018 were significantly greater at Brooks than at Lethbridge ($P < 0.001$).

The total N uptake, encompassing both tuber-N and canopy-N, differed across treatments in one of the four site-years. In Brooks-2018, urea + DMPSA resulted in a much greater total N uptake than that of biostimulant alone treatment (i.e., 407 vs. 293 kg N ha^{-1}; Table 5). Across the four site-years, potato tuber N uptake at harvest average 181 ± 6 kg N ha^{-1} yr^{-1}, which is comparable to the applied rate of N fertilizer (i.e., 200 kg N ha^{-1} yr^{-1}).

The estimates of NUE, HI and NHI in our study showed no significant effects across fertilizer treatments (Table 6). Overall, NUE varied between experimental years at Lethbridge (2017 < 2018) and between sites in 2017 (Lethbridge < Brooks) ($P < 0.001$). The treatment means of HI and NHI ranged from 0.55 to 0.71 and 0.41 to 0.67, respectively (Table 6).

Discussion

Impacts of N fertilization options on N_2O emissions

Major N_2O effluxes following N fertilizer addition in our study showed that the availability of soil N strongly influences the occurrence of peak N_2O emissions, which is consistent with previous studies (Burton et al., 2008; Gao et al., 2013). Most of these earlier studies evaluated only the influence of conventional fertilizers such as urea on N_2O emissions. Hutchinson et al. (2003) assessed the effect of ammonium nitrate (AN), urea, sulfur-coated urea and PCU on potato, but they focused only on the influence of these N sources on N use efficiency. Perron et al. (2019) measured denitrification rate from irrigated potato production on a coarse-textured soil in Eastern Canada when using fertilizers such as ammonium sulfate, AN and PCU. Our study documents, for the first time in the literature, how alternative N fertilizer formulations such as granular ASN and the novel DMPSA inhibitor impacts both N_2O fluxes and productivity in potato fields. When focusing on mitigation of N_2O emissions, the fact that the DMPSA inhibitor admixed with granular urea resulted in N_2O emissions comparable in magnitude with the emissions from unfertilized fields, and also much lower than in fields receiving urea alone supports the effectiveness of this new inhibitor formulation (Table 2, Fig. 4D). In one of the four site-years at Brooks-2018, DMPSA reduced the N_2O emissions from urea-amended fields by 57% (Table 2, Fig. 4D). Thilakarathna and Hernandez-Ramirez (2021) asserted that DMPSA effectively delivers emission reductions, conserves N in the soil, and inhibits the first enzymatic step of nitrification in part because the presence of the succinyl group in DMPSA decreases molecule volatility and extends its activity (Lin and Hernandez-Ramirez, 2020; Thilakarathna and Hernandez-Ramirez, 2021).

Among the different fertilizer treatments, both urea and ASN were applied with and without additives in this study. Overall, the urea treatment showed more N_2O emissions than the ASN treatment. Urea alone treatment resulted in greater concentrations of available N in both the soil solution and plant petioles in comparison to ASN (Fig. 2C and Fig. 2D). Van Groenigen et al. (2010) and Chai et al. (2020) concurrently reported that N surpluses can raise N_2O emissions by generating a higher risk for N losses. Although the mitigating effects of DMPSA were not always evident, using DMPSA admixed with either urea or ASN tended to reduce overall N_2O emissions.

Previous studies have shown the beneficial role of ESN in enhancing potato yield and simultaneously reducing N_2O emissions (Gao et al., 2015; Ghosh et al., 2019; Hutchinson et al., 2003). In contrast, some studies showed no significant reduction of N_2O emissions and yield improvement when using ESN (Gao et al., 2017; Zebarth et al., 2012). In our study, even though

N_2O emissions from ESN were not statistically different from other treatments, the magnitude of N_2O emissions from the furrows in 2017 at Lethbridge was considerably high. The N released from ESN involves movement of soil water to the fertilizer granule, dissolution of urea inside the ESN granule, and diffusion of urea-N to the soil solution. In other words, the role of ESN in minimizing N_2O emissions and enhancing NUE is highly regulated by soil moisture fluctuations (Thilakarathna et al., 2021). Sharp moisture increases in the furrows following a major rainfall or irrigation event can contribute to high N_2O fluxes in Lethbridge as triggered by higher soil moisture. The ESN in our study was also applied all as a single pre-planting fertilizer application, which may have resulted under certain cases in no significant reduction of N_2O emissions and null yield improvement by ESN. Hence, future research could evaluate the responses of coated N fertilizers applied at the emergence of potato seedlings instead of full applications at pre-planting.

Our field data provide regional N_2O EF_{area} for potato crops under a broad range of N fertilizer formulation options (Table 2). Thilakarathna et al. (2021) reported EF_{area} for numerous fertilizer formulations in spring wheat fields fertilized at 100 kg N kg^{-1} in Central Alberta. Their study estimated mean EF_{area} of 0.31% while accounting for the whole annual cycle. In the present study, EFs were much lower than reported by both Thilakarathna et al. (2021) and Chai et al. (2020) based on EF_{area} calculated encompassing flux measurements during the potato growing seasons (i.e., ~May to October). It is noted that the relatively elevated cumulative N_2O emissions from our control plots were also drivers of the low growing-season EF_{area} found in the present study, which averaged 0.056 % (Table 2). By contrast, based on estimations of EF using an exponential equation model proposed by Rochette et al. (2018) and Liang et al. (2020), the growing-season 2-year mean N_2O EF as a function of total water addition (rainfall + irrigation) resulted in 0.77% and 0.60% at Lethbridge and Brooks, respectively (Table 1). In comparison to our study, Chai et al. (2020) recently reported a lower estimate of N_2O EF (0.41%) as a function of total water input in irrigated wheat and canola sites also located in Lethbridge. Essentially, irrigations of 373 mm in Lethbridge and 344 mm in Brooks (Table 1) are much higher than the 162 mm irrigation used by Chai et al. (2020). Compared to other irrigated crops such as wheat and canola, irrigated potato soils can stay relatively wetter over longer periods – a condition known to be conducive to increase N_2O production (Roman-Perez and Hernandez-Ramirez, 2021; Thilakarathna et al., 2021).

Distinct microenvironments between hills and furrows within potato fields affect N_2O emissions (Burton et al., 2008). In our study, calculations of EFs for hill and furrow positions separately (data not shown) further showed that emissions from furrows (e.g., Lethbridge-2017; Fig. 4) were the main contributors to high EFs. This clearly indicated the need of implementing management practices targeted at mitigating these hot spots of N_2O emissions from the furrows.

In potato production, the in-crop hilling operation is done to further provide loosened and well aerated soils for better tuber growth, tuber greening prevention by covering from sunlight, weed control, and to subsequently facilitate potato harvesting (Gao et al., 2013). Additionally, hilling can also cause the formation of differential microsites within potato fields (i.e., hills vs. furrows within the crop management zone). These differences between hills and furrows include soil bulk density, aeration, water-filled pore space, C and N concentrations, microbial communities, and N_2O production processes (Zebarth and Milburn, 2003). Greater N_2O emissions observed from furrows at Lethbridge can be primarily associated with denitrification source. Water from rainfall and irrigation accumulates more in furrows than in potato hills (Harms and Konschuh, 2010). Broadcast N fertilizer enters furrows as well as N runoff from hills. The water and N accumulation in furrows can be further enhanced by the low uptake of water and N from the furrows by potato plants as the root systems are mainly concentrated in the hills. It is postulated that precise placement of pre-plant N fertilizer localized only where potato hills would be formed can increase N utilization by plants and probably reduce losses to the environment. This hypothesis requires further field testing.

In comparison to Brooks, Lethbridge soils have greater C and N substrates (10 ± 0.9 vs. 14 ± 0.7 g C kg^{-1} soil, and 1.1 ± 0.1 vs. 1.4 ± 0.1 g N kg^{-1}, respectively). This different across sites in soil organic C and N concentrations can imply greater mineralization of organic matter and associated N, leading to increased background N in Lethbridge soils, which likely contribute to overall N_2O production over the growing seasons (Daly and Hernandez-Ramirez, 2020; Roman-Perez and Hernandez-Ramirez, 2021). When C and N are available simultaneously in hypoxic furrows, greater fluxes of N_2O can be produced due to denitrification (Smith et al., 1998; Thilakarathna and Hernandez-Ramirez, 2021). When comparing the two experimental sites, C availability could become a limiting factor for N_2O production from furrows at Brooks. When a soil is characterized by relatively lower C, the potato rhizosphere in the hills, being an important C source in the hills in comparison to the furrows, can enhance the N_2O production from hills via heterotrophic denitrification. Furthermore, it is possible that any produced N_2O can easily escape from the hills because mechanical soil loosening had temporally improved porosity and pore connectivity (Burton et al., 2008).

Our experiment examined a biostimulant that contained primary N-fixing microorganisms (*Azotobacter vinelandii* and *Clostridium pasteurianum*) as well as secondary microbes (e.g., *Nitrosomonas, Nitrobacter, Nitrococcus, Rhizobium*) with the aim of raising soil N availability, root growth and plant uptake. These putative effects were collectively expected to increase plant productivity, which was not found in our study. Moreover, it was observed that the biostimulant alone as well as the biostimulant in combination with urea or ASN had overall no effect on N_2O emissions. However, in certain cases, these biostimulant treatments even seemed to increase N_2O emissions numerically. For instance, this was noted when comparing cumulative fluxes from biostimulant-urea vs. urea alone. This finding is in line with Souza et al. (2019) who reported increased N_2O emissions in potato fields that had received additions of an N-fixing biostimulant. Additionally, when a biostimulant is applied in fields that also receiving urea additions, the production of toxic NH_3 from urea hydrolysis can detrimentally impact inoculated microbes (Calvo et al., 2013; Calvo et al., 2014). These earlier studies had actually shown a beneficial role of certain biostimulants that contained phenolic compounds in minimizing N_2O emissions when applied specifically with urea-ammonium nitrate (Calvo et al., 2013; Calvo et al., 2014); however, this effect was absent in our study. Furthermore, potato production systems are characterized by high input, productivity, nutrient extraction, and soil disturbance. Therefore, these soils under potato cropping can have a distinct microbial community that has been selected and trained over time to these unfavorable, fluctuating conditions. Adapting rapidly to such adverse environment can be a challenge for the microbes present in applied biostimulants.

Potato productivity as a function of N fertilization choices

This study found that marketable yield of potato was equally enhanced by both ASN admixed with DMPSA and ESN fertilization options, with 36% consistently higher productivity than the unfertilized fields in one of the four site-years (i.e., Lethbridge-2018; 45 vs. 33 Mg ha^{-1}, Table 4). The fact that these two fertilizer alternatives to using urea alone resulted in this coherent productivity advantage is insightful for enhancing N management in potato. For several practical reasons, granular is the most commonly used N fertilizer across Western Canada

(Guenette et al., 2019; Thilakarathna et al., 2021), and hence, this represents an opportunity to enhance potato productivity regionally, with a 25% likelihood based on the four available site-years in our study.

Even though the potato cultivar and seed source were the same at both study sites, we initially expected higher yields from Lethbridge than Brooks. The seeding of potato in Lethbridge took place earlier than Brooks, and Lethbridge also experienced a growing season with more cumulative physiological growing degree days (P-Days). Differences in environmental conditions and soils as noted above can have caused variations in potato productivity between the four experimental site-years in our study. For instance, the Lethbridge site contained high concentrations of organic matter as noted above, which may have also generated additional N mineralization and availability.

In 2017, the marketable yields from both sites were similar. Total yield is in part the reflection of the capacity of the mechanical harvesting equipment to pick up undersized tubers. Different harvesters were used at the two experimental sites in 2017. The harvester used at Lethbridge may have left more small tubers in the field relative to Brooks, which likely resulted in a lower total yield at Lethbridge. In 2018, due to the previous observation of leftover tubers in the field in 2017, tubers missed by the mechanical harvester at both sites were collected by hand to assure improved accountability of potato productivity during the experimental year 2018.

Biomass production, accumulation and partitioning of crops depend on multiple factors such as the cultivar, air temperature, availability of water and nitrogen, and photoperiod (Geremew et al., 2007; Hernandez-Ramirez et al., 2011). In our study, overall potato DM partition to tubers averaged 63%, ranging from 55% to 71% (Table 6). These results were slightly lower than HIs previously reported by Bélanger et al. (2001) who found HIs between

0.62 and 0.77 for potato crops receiving 250 kg fertilizer-N ha^{-1} across varying genotypes and irrigation managements.

In general, potato N use-efficiencies were 3 % of applied fertilizer-N at Lethbridge and 7 % at Brooks. The NUE calculations in our study involved the subtraction of potato productivity from the control in the N fertilizer treatment. The low NUE results observed across the four site-years can be explained by the high total tuber yield measured in the unfertilized control fields. More specifically, focusing on the overall lowest NUE result of -0.13 % at Lethbridge-2017 (Table 4), the total tuber yield of the control fields was greater than total tuber yield of most fertilizer treatments, which also indicates greater availability of mineralized N in the Lethbridge soils as noted above.

Plant petioles store and transport nitrate (Vitosh and Silva, 1994). Petiole nitrate analysis has proven to be a sensitive indicator of potato N status temporally throughout the growing season (Meyer and Marcum, 1998). Similar to previous studies, petiole nitrate in our two experimental sites during both years were highest in the early growing season and gradually declined thereafter. High petiole nitrate concentrations in the beginning of the growing season can be caused by the accumulation of soluble N in the haulm prior to potato tuberization. The rapid decrease of petiole N later over the growing seasons indicated the translocation and redistribution of accumulated N as both tuber formation and size expansion gradually become larger N sinks within the plants (Porter and Sisson, 1993). In our study, petiole nitrate concentrations increased in response to N fertilization, which provides evidence for the availability of broadcast-incorporated N in the root zone. Variation of petiole nitrate concentrations across the study sites can indicate the difference in soil and weather conditions among sites to supply available N. It became clearly evident that high N availability in these soils results in greater petiole nitrate concentrations based on established relationships (Fig. 5).

Conclusion

Urea alone typically resulted in the highest N_2O fluxes. This finding is concerning because urea is the most common N fertilizer used in potato production, and also overall within Western Canada across all cropping systems. Nevertheless, the results from our study further showed that DMPSA inhibitor admixed with either granular urea or ASN can effectively reduce N_2O emissions while maintaining potato tuber yield. This supports a change towards improved recommendations in fertilization management. The increased N_2O emissions associated with C and N rich soils and likely-hypoxic furrows suggest that irrigation water can be managed more precisely to minimize water accumulation in furrows, perhaps through localized and variable rate irrigation. Also, more water infiltration into the potato hill can be hypothetically increased by altering hills from the standard round shape into a flat-topped design. By comprehensively assessing the effect of N fertilizer options on N_2O emissions, N dynamics in soil solution and plant tissues, as well as potato productivity and NUE, the present study offers insights and inclusive recommendations for better management of recurrent N fertilization.

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Table 1. Estimated N_2O EF as a function of total water addition of rainfall and irrigation based on exponential equation N_2O EF % = $e^{(0.00558 \times H2O - 7.701)} \times 100$ (Rochette et al., 2018; Liang et al., 2020).

	Lethbridge			Brooks		
Water addition	2017	2018	2-yr mean	2017	2018	2-yr mean
May to Oct						
Rainfall (mm)	175	150	163	148	127	138
Irrigation (mm)	368	378	373	366	322	344
Rainfall + irrigation (mm)	543	529	536	514	450	482
EF_{H2O} (% kg N_2O-N kg^{-1} fertilizer)	0.936	0.865	0.901	0.798	0.557	0.677
May to Sep						
Rainfall (mm)	128	136	132	120	117	118
Irrigation (mm)	368	379	373	366	322	344
Rainfall + irrigation (mm)	496	515	506	486	439	462
EF_{H2O} (% kg N_2O-N kg^{-1} fertilizer)	0.719	0.801	0.760	0.680	0.525	0.602

Table 2. Cumulative growing season N_2O emissions (g N_2O-N ha^{-1}), area-based N_2O emission factors (EF_{area}) (% kg N_2O-N kg^{-1} N fertilizer) and yield-based emission factors (EF yield) (g N_2O-N Mg^{-1} tuber) of potato fields at Lethbridge and Brooks during 2017 and 2018. SE stands for standard error of the means (n= 4).

N treatment	Cumulative N_2O emissions (g N_2O-N ha^{-1})				EF_{area} (% kg N_2O-N kg^{-1} N fertilizer)				EF yield (g N_2O-N Mg^{-1} tuber)			
	Lethbridge		Brooks		Lethbridge		Brooks		Lethbridge		Brooks	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Control	515	208	85	64a§					11.045	3.705	1.641	0.945a
Biostimulant	543	n.d.	73	n.d.	-0.018	n.d.	-0.011	n.d.	11.025	n.d.	1.449	n.d.
Urea	623	279	87	256c	0.023	0.020	-0.004	0.010b	13.782	5.105	1.550	3.098b
Urea + DMPSA †	778	252	85	154a	0.100	-0.001	-0.005	-0.009a	14.454	4.539	1.592	1.774ab
Urea + Biostimulant	544	n.d.	131	n.d.	-0.017	n.d.	0.018	n.d.	11.605	n.d.	2.278	n.d.
Urea + DMPSA + Biostimulant	588	n.d.	85	n.d.	0.005	n.d.	-0.005	n.d.	12.241	n.d.	1.448	n.d.
Ammonium sulfate nitrate (ASN)	443	241	85	171b	-0.067	-0.006	-0.005	0.003ab	9.232	4.363	1.544	2.412ab
ASN + DMPSA	420	260	76	168b	-0.079	0.002	-0.009	0.002ab	9.085	4.333	1.297	1.971ab
ESN‡ (polymer coated urea)	745	296	143	192b	0.084	0.012	0.024	0.040ab	15.373	5.077	2.574	2.310ab
Overall mean ± SE	578±96	256±41	94±27	165±16	0.004±0.05	0.006±0.01	0.001±0.01	0.009±0.008	11.982±2.39	4.683±0.538	1.708±0.532	2.313±0.327
ANOVA P-value												
N treatment	0.300	0.726	0.557	0.001	0.209	0.820	0.460	0.031	0.573	0.110	0.719	0.008

§ Differences across treatments, indicated by different lowercase letters, were determined via Tukey's Honest Significant Difference after significant ANOVAs at the alpha critical level of 0.05.

† DMPSA stands for 2,4-dimethylpyrazol succinic acid.

‡ ESN stands for Environmentally Smart N.

Table 3. Potato tuber and canopy total N concentration at maturity at Lethbridge and Brooks in 2017 and 2018. SE stands for standard error of the means (n= 4).

N treatment	Lethbridge				Brooks			
	2017		2018		2017		2018	
	Tuber N (%)	Canopy N (%)	Tuber N (%)	Canopy N (%)	Tuber N (%)	Canopy N (%)	Tuber N (%)	Canopy N (%)
Control	1.58	1.61	0.83	2.00	1.30	1.59	1.36	1.61
Biostimulant	1.73	1.45	1.03	1.97	1.40	1.58	1.20	1.61
Urea	1.74	1.74	1.07	2.17	1.48	1.75	1.24	1.51
Urea + DMPSA †	1.66	1.62	0.98	2.17	1.45	1.70	1.27	1.67
Urea + Biostimulant	1.76	1.54	0.89	2.06	1.49	1.86	1.16	1.60
Urea + DMPSA + Biostimulant	1.66	1.73	1.07	1.87	1.39	1.86	1.25	1.66
Ammonium sulfate nitrate (ASN)	1.80	1.62	0.92	2.23	1.46	1.70	1.32	1.75
ASN + DMPSA	1.61	1.65	1.07	2.11	1.53	1.84	1.27	1.46
ASN + Biostimulant	1.57	1.52	1.14	2.07	1.37	1.80	1.24	1.51
ASN + DMPSA + Biostimulant	1.65	1.64	0.86	2.01	1.44	1.85	1.30	1.62
ESN ‡ (polymer coated urea)	1.61	1.57	0.99	2.14	1.51	1.85	1.30	1.76
Overall mean ± SE	1.67±0.07	1.61±0.08	0.98±0.09	2.07±0.11	1.44±0.09	1.76±0.11	1.27±0.07	1.61±0.12
ANOVA P-value								
N treatment	0.244	0.438	0.302	0.494	0.780	0.455	0.726	0.741

† DMPSA stands for 2,4-dimethylpyrazol succinic acid.

‡ ESN stands for Environmentally Smart N.

Table 4. Total yield mean tuber mass and specific gravity of potatoes harvested from experimental plots at Lethbridge and Brooks grown with alternative nitrogen fertilizer formulations in 2017 and 2018. These are fresh potato weights. SE stands for standard error of the means (n= 4).

N treatment	Lethbridge								Brooks							
	Total yield ($Mg\ ha^{-1}$)		Total marketable yield ($Mg\ ha^{-1}$)		Mean tuber mass (g)		Specific gravity ($g\ mL^{-1}$)		Total yield ($Mg\ ha^{-1}$)		Total marketable yield ($Mg\ ha^{-1}$)		Mean tuber mass (g)		Specific gravity ($g\ mL^{-1}$)	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Control	49	50	39	33b§	195	167ab	1.082	1.092	54	69	30	51	187	196	1.098	1.098
Biostimulant	48	53	36	34ab	201	170ab	1.083	1.093	51	68	30	53	191	198	1.095	1.097
Urea	46	53	37	39ab	209	181ab	1.082	1.094	58	80	41	69	206	230	1.098	1.088
Urea + DMPSA†	54	54	45	40ab	213	176ab	1.083	1.088	56	83	37	72	194	224	1.101	1.090
Urea + Biostimulant	47	54	38	41ab	208	184ab	1.083	1.094	57	82	41	71	200	230	1.096	1.092
Urea + DMPSA + Biostimulant	51	54	40	38ab	202	176ab	1.084	1.092	59	77	38	64	208	232	1.095	1.090
Ammonium sulfate nitrate (ASN)	48	54	38	41ab	194	193a	1.083	1.093	57	71	39	59	204	218	1.095	1.093
ASN + DMPSA	47	58	37	45a	203	184ab	1.079	1.089	60	84	39	69	196	218	1.092	1.091
ASN + Biostimulant	50	56	43	42ab	222	162b	1.085	1.095	57	75	43	64	215	232	1.097	1.088
ASN + DMPSA + Biostimulant	50	57	38	41ab	197	167ab	1.085	1.091	62	76	43	65	219	221	1.093	1.090
ESN‡ (polymer coated urea)	52	58	43	45a	214	193a	1.083	1.091	57	78	40	67	202	227	1.095	1.093
Overall mean ± SE	49±1	55±1	39±1	40±1	205±3	178±4	1.083±0.0005	1.092±0.0005	57±1	77±2	38±1	64±1	202±3	221±5	1.096±0.0007	1.092±0.0009
ANOVA P-value																
N treatment	0.829	0.434	0.730	0.017	0.593	0.005	0.146	0.271	0.645	0.234	0.329	0.490	0.258	0.690	0.217	0.201

§ Differences across treatments, indicated by different lowercase letters, were determined via Tukey's Honest Significant Difference after significant ANOVAs at the alpha critical level of 0.05.

† DMPSA stands for 2,4-dimethylpyrazol succinic acid.

‡ ESN stands for Environmentally Smart N.

Table 5. Potato tuber, canopy, and total N uptake at harvest at Lethbridge and Brooks in 2017 and 2018. SE stands for standard error of the means (n= 4).

N treatment	Lethbridge						Brooks					
	2017			2018			2017			2018		
	N canopy	N tuber	N uptake	N canopy	N tuber	N uptake	N canopy	N tuber	N uptake	N canopy	N tuber	N uptake
	--- kg N ha^{-1} ---											
Control	93	179	272	134	95	230	113	159	273	104	214	318 ab§
Biostimulant	100	192	293	132	125	257	165	167	332	107	186	293 a
Urea	91	184	275	175	133	308	152	194	345	165	228	394 ab
Urea + DMPSA†	113	206	288	153	122	275	128	189	317	164	243	407 b
Urea + Biostimulant	135	190	325	152	111	264	182	196	378	123	219	341 ab
Urea + DMPSA + Biostimulant	100	192	293	128	130	258	204	188	392	164	220	385 ab
Ammonium sulfate nitrate (ASN)	106	200	306	165	113	278	193	189	382	169	217	386 ab
ASN + DMPSA	102	177	278	167	143	310	229	210	439	136	243	379 ab
ASN + Biostimulant	90	178	267	138	147	285	162	181	343	125	213	337 ab
ASN + DMPSA + Biostimulant	126	187	312	174	112	285	207	205	412	144	230	374 ab
ESN‡ (polymer coated urea)	102	192	298	132	129	261	165	198	362	159	234	393 ab
Mean	105	189	291	150	124	274	173	189	361	142	222	364
S.E.	5	4	7	6	4	8	8	5	11	6	5	9
ANOVA P-value for N treatment	0.737	0.883	0.618	0.779	0.204	0.716	0.102	0.554	0.064	0.098	0.420	0.027

§ Differences across treatments, indicated by different lowercase letters, were determined via Tukey's Honest Significant Difference after significant ANOVAs at the alpha critical level of 0.05.

† DMPSA stands for 2,4-dimethylpyrazol succinic acid.

‡ ESN stands for Environmentally Smart N.

Table 6. Nitrogen use efficiency (NUE), dry matter harvest index (DM HI), and NHI partitioning of potato crops at Lethbridge and Brooks in 2017 and 2018. SE stands for standard error of the means (n= 4).

N treatment	NUE (kg total potato tuber kg^{-1} N fertilizer)				HI (kg tuber DM kg^{-1} tuber+canopy DM)				NHI (kg tuber N kg^{-1} tuber+canopy N)			
	Lethbridge		Brooks		Lethbridge		Brooks		Lethbridge		Brooks	
	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018	2017	2018
Control	--	--	--	--	0.66	0.64	0.64	0.71	0.66	0.42	0.60	0.68
Biostimulant	-1.19	2.93	-2.82	-0.96	0.62	0.65	0.60	0.70	0.66	0.49	0.50	0.64
Urea	-4.26	3.16	4.24	13.28	0.66	0.60	0.55	0.63	0.67	0.43	0.56	0.58
Urea + DMPSA†	5.32	4.63	1.88	16.43	0.63	0.64	0.57	0.67	0.63	0.44	0.59	0.61
Urea + Biostimulant	-2.75	4.63	3.71	15.40	0.58	0.63	0.57	0.71	0.59	0.42	0.53	0.63
Urea + DMPSA + Biostimulant	1.51	4.10	6.14	9.30	0.66	0.65	0.58	0.65	0.66	0.51	0.49	0.58
Ammonium sulfate nitrate (ASN)	-1.53	4.28	3.25	2.89	0.63	0.63	0.58	0.63	0.66	0.41	0.50	0.56
ASN + DMPSA	-2.44	8.86	6.69	17.06	0.63	0.63	0.60	0.67	0.63	0.46	0.48	0.64
ASN + Biostimulant	0.92	6.76	3.98	7.21	0.66	0.66	0.56	0.67	0.67	0.51	0.53	0.63
ASN + DMPSA + Biostimulant	0.48	7.47	9.09	8.75	0.60	0.63	0.58	0.67	0.60	0.42	0.50	0.61
ESN‡ (polymer coated urea)	2.64	8.54	3.90	10.97	0.60	0.68	0.56	0.67	0.64	0.50	0.55	0.60
Overall mean ± SE	-0.13±4.28	5.54±2.64	4.01±3.48	10.03±5.04	0.63±0.01	0.64±0.01	0.58±0.01	0.67±0.01	0.64±0.01	0.46±0.01	0.53±0.01	0.62±0.01
ANOVA P-value												
N treatment	0.806	0.692	0.594	0.396	0.921	0.633	0.834	0.099	0.905	0.300	0.412	0.402

† DMPSA stands for 2,4-dimethylpyrazol succinic acid.

‡ ESN stands for Environmentally Smart N

Figures

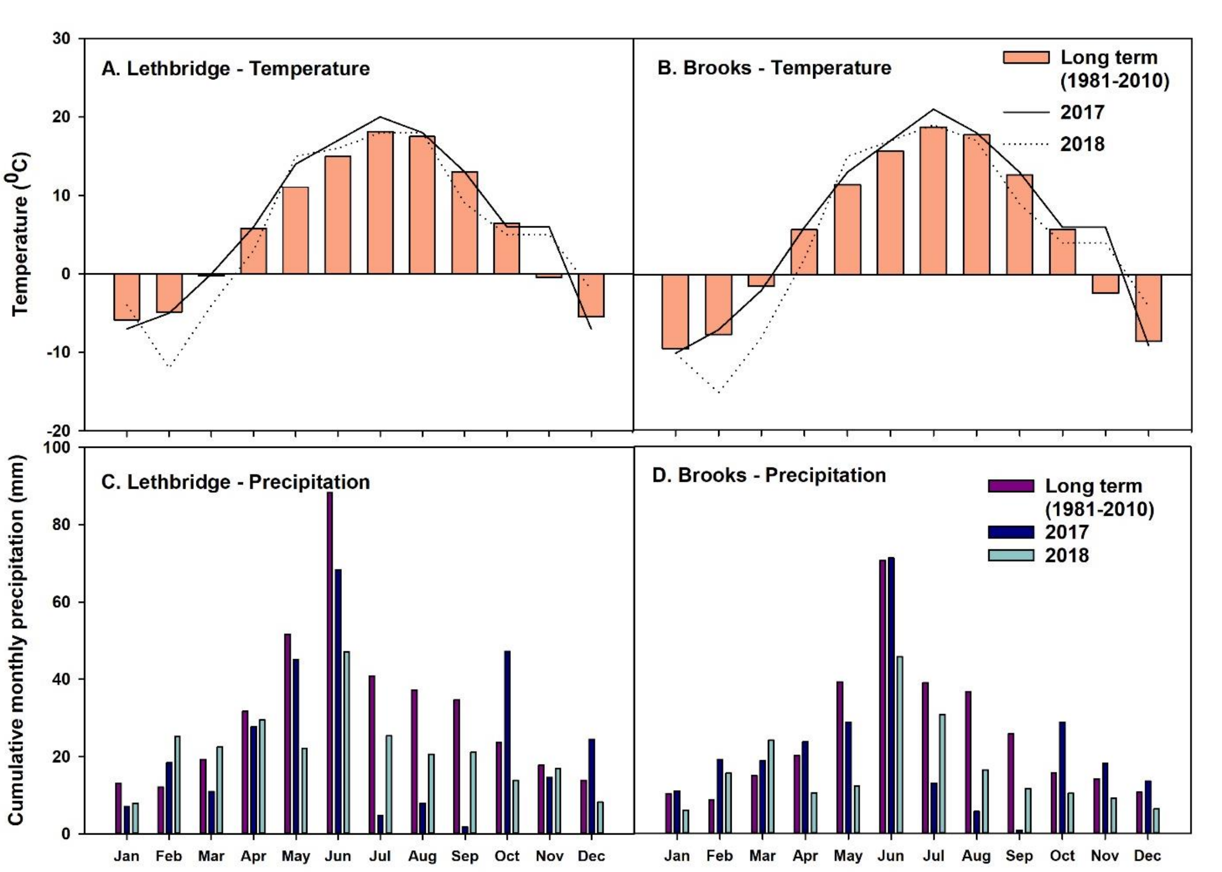

Fig. 1. Monthly average air temperature and cumulative precipitation and at Lethbridge (A, C) and Brooks (B, D) for year 2017, 2018 and the 30-year normal monthly data.

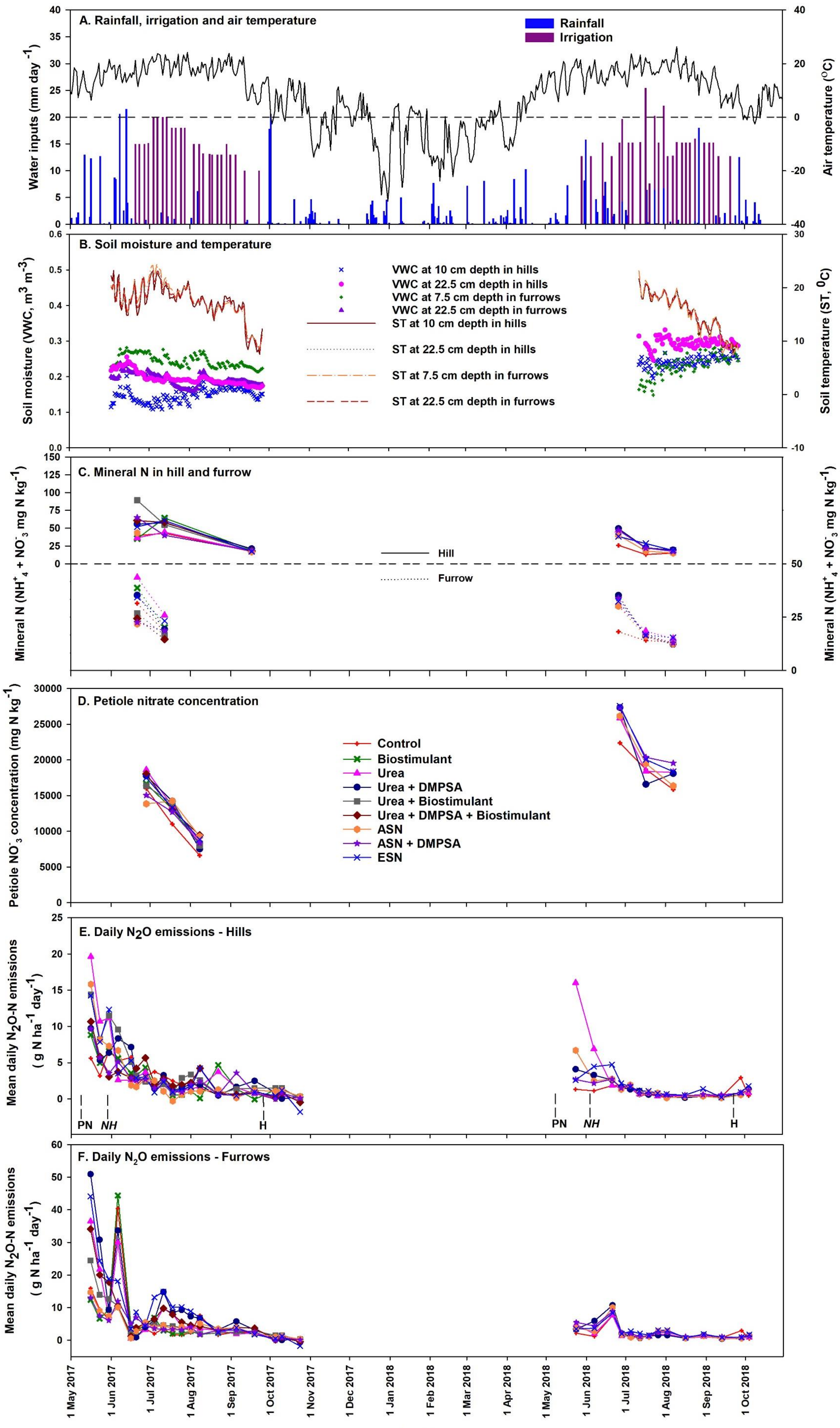

Fig. 2. (A) Daily average air temperature and water inputs (precipitation and irrigation), (B) soil moisture and soil temperature in the potato hills at the depths of 10 and 22.5 cm as well as in the furrows at 7.5 and 22.5 cm, (C) soil ammonium and nitrate concentrations in potato hill and furrow, (D) potato petiole N concentration, daily N_2O fluxes from (E) hills and (F) furrows across N treatments at Lethbridge during 2017 and 2018 growing seasons. All experimental treatments were measured in the growing season 2017, while a subset of selected treatments were measured in the growing season 2018. In panel B, VWC and ST stand for volumetric water content and soil temperature, respectively. In Panel E, the acronyms PN, NH and H near the horizontal axis indicate the dates of pre-planting N fertilization, post-planting N fertilization followed by hilling, and harvesting.

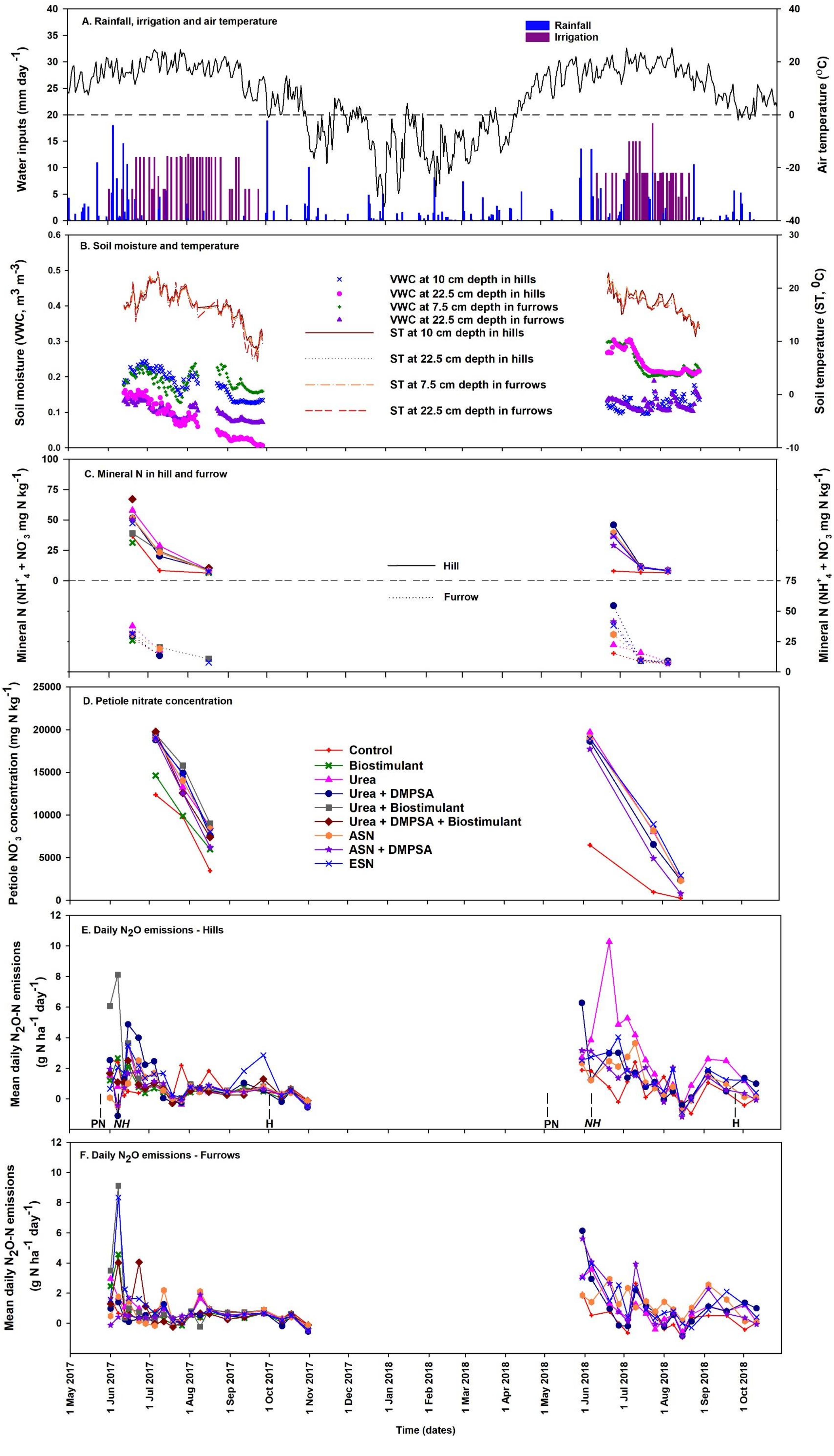

Fig. 3. (A) Daily average air temperature and water inputs (precipitation and irrigation), (B) soil moisture and soil temperature in the potato hills at the depths of 10 and 22.5 cm as well as in the furrows at 7.5 and 22.5 cm, (C) soil ammonium and nitrate concentrations in potato hill and furrow, (D) potato petiole N concentration, daily N_2O fluxes from (E) hills and (F) furrows across N treatments at Brooks during 2017 and 2018 growing seasons. All experimental treatments were measured in the growing season 2017, while a subset of selected treatments were measured in the growing season 2018. In panel B, VWC and ST stand for volumetric water content and soil temperature, respectively. In Panel E, the acronyms PN, NH and H near the horizontal axis indicate the dates of pre-planting N fertilization, post-planting N fertilization followed by hilling, and harvesting.

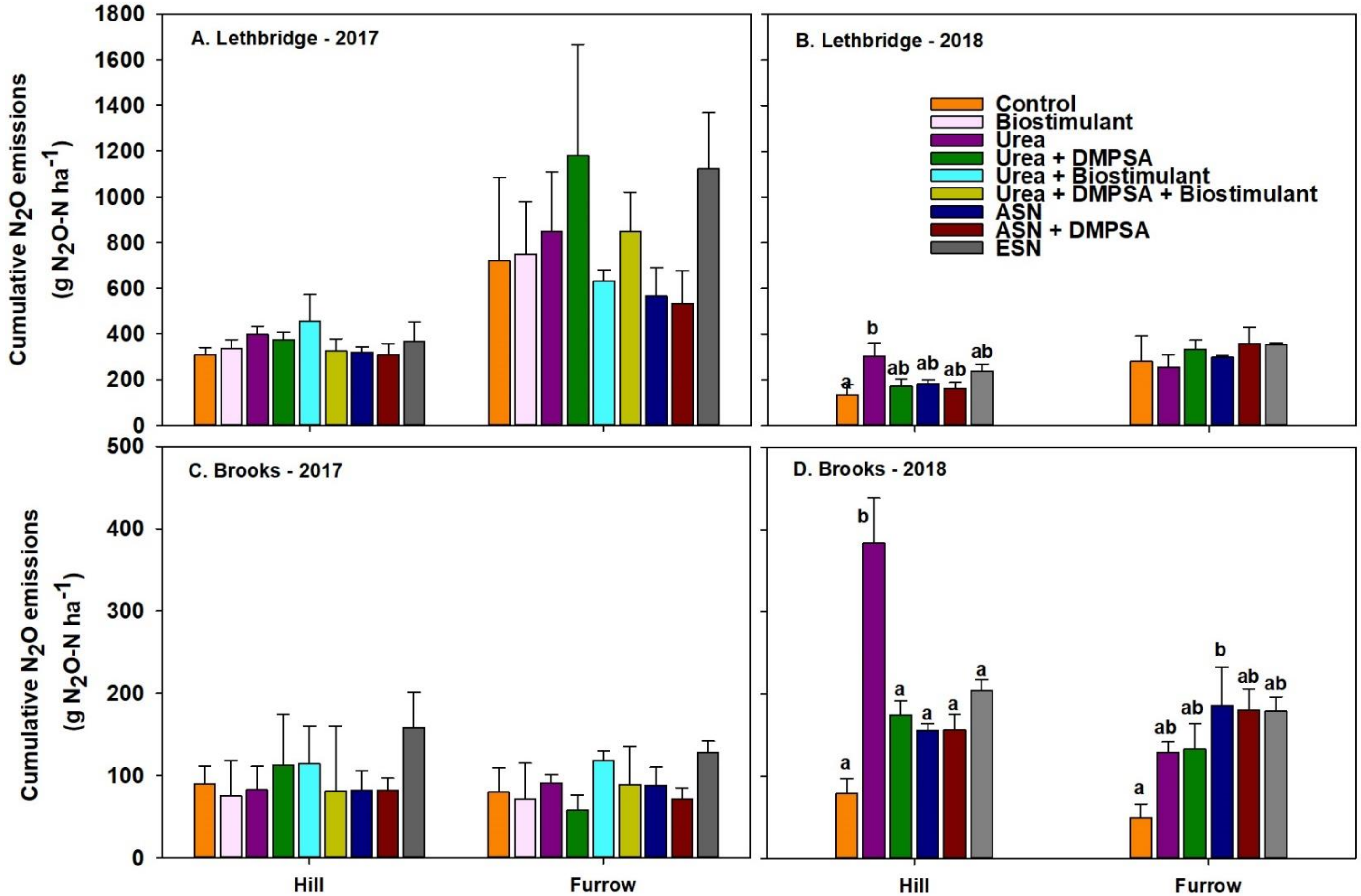

Fig. 4. Cumulative N_2O emissions of different N fertilizers from hill and furrow at Lethbridge (A), (B) and Brooks (C), (D) during the growing seasons of 2017 and 2018. All treatments were measured in 2017, while a subset of selected treatments were measured in 2018. The differences across treatments, indicated by different lowercase letters, were determined via Tukey's Honest Significant Difference at the alpha level 0.05. Error bars correspond to standard errors of the means. In the legend, acronyms ASN, DMPSA, and ESN stand for ammonium sulfate nitrate, 2,4-dimethylpyrazol succinic acid, and Environmentally Smart N.

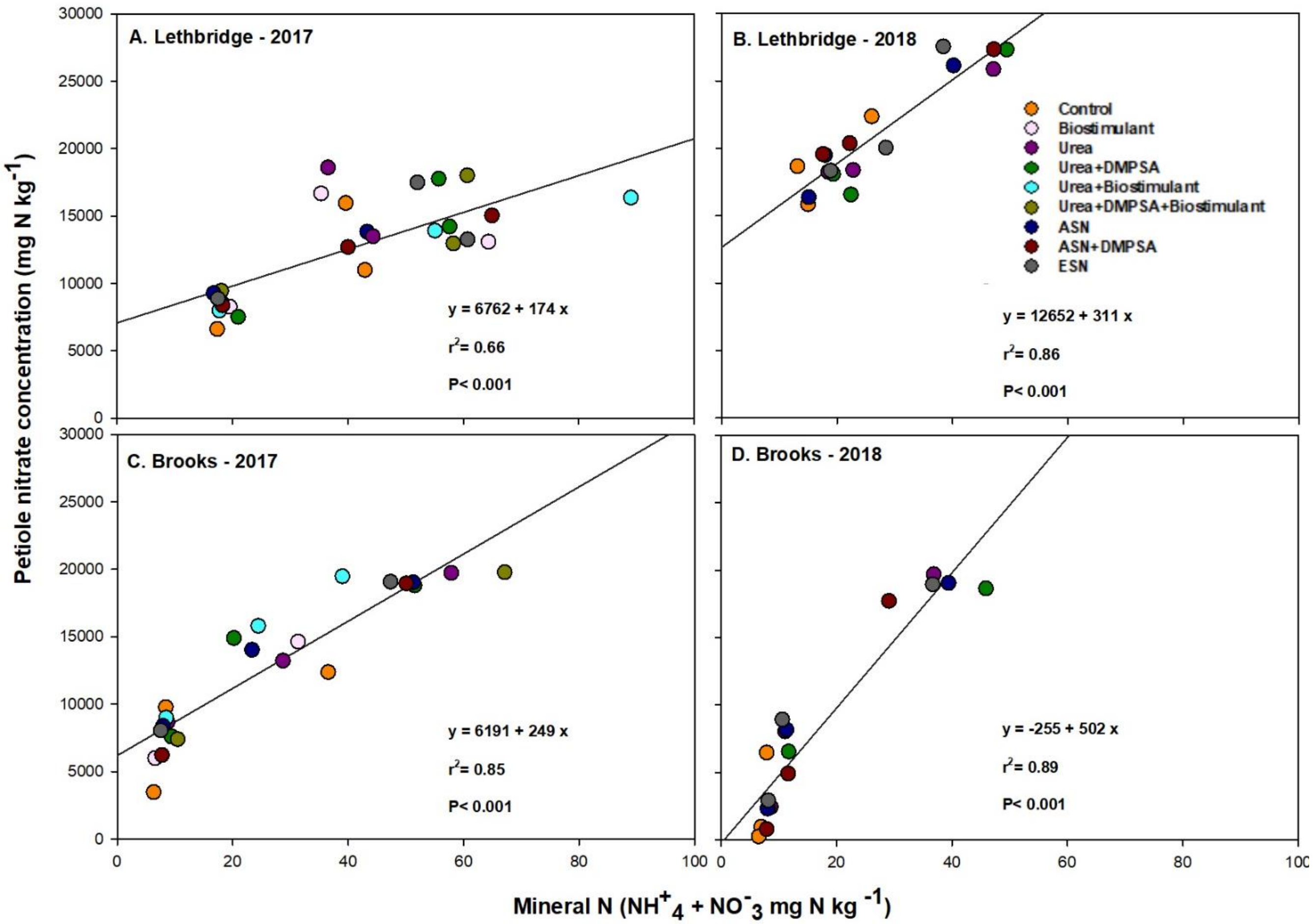

Fig. 5. Relationships between potato petiole nitrate concentration and soil ammonium plus nitrate at Lethbridge (A and B) and Brooks (C and D) over 2017 (A and C) and 2018 (B and D). The datasets are shown as time series in Fig. 2C, Fig. 2D, Fig. 3C, and Fig. 3D. All treatments were measured in 2017, while a subset of selected treatments were measured in 2018.