ADF Project Progress Report

1. Project title and ADF file number.

ADF File No. 20180193: *Balancing Agronomic and Environmental Outcomes Using Enhanced Efficiency Nitrogen Fertilizers*

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4. Abstract/Summary

The amount and scheduling of fertilizer applications are key controls on the timing and magnitude of N_2O emissions, with fall-applied N believed to be more prone to N losses—particularly as denitrification-induced N_2O emissions when the soil thaws and soil moisture, temperature, and N availability increase. For this reason, fall N applications are thought to be inferior to spring N applications and are generally not considered a sustainable N practice under the Nitrous oxide Emissions Reduction Protocol (NERP). Nevertheless, some canola growers in the Canadian prairies still opt for fall applications due to time and labour management issues. To address sustainability issues, producers are looking to enhanced efficiency N fertilizer (EENF) products to reduce N_2O and protect crop yield. Yet, there is little information regarding the agronomic and environmental performance of EENFs for dryland canola production in western Canada. To address this knowledge gap, we conducted a three-year (two growing seasons) study to evaluate and compare the performance of two stabilized EENF products (SuperU and eNtrench) with that of conventional granular urea—with all products applied in the fall or spring and at the soil test recommendation (STR) or at 70% of the STR. The results of this study were significantly impacted by drought conditions in 2020 and 2021, with yields that were about 30% and 90% lower than target yields in 2020 and 2021, respectively. In terms of agronomic performance, the EENFs had no effect on either yield or nitrogen use efficiency. Likewise, rate effects were generally not significant, though the was a small yield depression with the spring application of urea/eNtrench at the reduced N rate (i.e., at 70% of the soil test

recommendation). In 2021, there was no recoverable yield in about one-third of the plots that received fall N applications and about two-thirds of the plots that received spring N applications. This was indicative of a significant timing effect, with yields being greater when the fertilizer was applied in the fall relative to the spring, and was attributed to better moisture retention in the fall-tilled plots. Daily N_2O emissions followed a typical event-based–background pattern with major emission events coinciding with snowmelt/spring thaw and the spring seeding/fertilizer operations. For fall N application, the magnitude of emissions during the spring thaw was determined by environmental and soil conditions both during the overwinter period and at snowmelt/thaw (ST) in the early spring and cumulative ST emissions were much greater in 2020 than in 2021. Cumulative ST emissions associated with the fall N applications were generally greater than those associated with the spring N applications—reflecting differences in both soil and environmental conditions and available N supply. However, there were no N source or rate effects on the cumulative ST emissions in either year. Growing season (GS) emissions were generally greater following spring N applications than fall N applications, which was to be expected, but the difference was significant only in 2020 when soil moisture was less limiting. Also in 2020, there were significant N source and rate effects on cumulative GS emissions, with the EENFs generating lower emissions than the conventional urea and with emissions decreasing as the N rate increased. In 2021, total annual emissions were dominated by non-growing season (NGS) emissions—especially those occurring in response to late-season rains after harvest. Moreover, during this period the EENF products were more effective at reducing N_2O emissions, though because emissions were quite low throughout the growing season, the differences were also small and significant emissions reductions were achieved only with the urea/eNtrench. While our study provides new data on the performance of two of common EENF products, results of the study were severely impacted by significant moisture deficiencies in both years and, hence, are not reflective of what producers might expect in a "normal" year. Nevertheless, and with this caveat in mind, our results provide strong evidence that the primary targets for emissions reductions in western Canada should be the controls on emissions occurring at spring thaw and enhanced synchronization of N supply with crop N demand.

5. Extension Messages

- Emissions of N_2O, a potent greenhouse gas, occur even under drought conditions.
- Late season rains can trigger significant N_2O emissions under conditions where crop N removal is limited.
- Non-growing season N_2O emissions contribute a disproportionately large fraction of total annual emissions.
- Management options aimed at N_2O emissions reductions should target enhanced synchronization of N supply with crop N demand and the emissions occurring at spring thaw.

6. Introduction

Driven by consumer demands for "green" products, sustainability has become a key part of the marketing landscape. For example, establishing the environmental sustainability of crop production practices is critical to accessing biofuels markets in both Europe (EU Renewable Energy Directive) and the United States (US Renewable Fuel Standard). As well, in 2016 Walmart, the world's largest grocery retailer, launched Project Gigaton with a goal of reducing GHG emissions in its supply chain by 1 Gt by 2030—including a reduction target of 300 Mt of GHG emissions from the agriculture sector through the adoption of "best-in-class" management practices. To meet these goals, all components of the agri-food supply chain (including producers) must be able to (i) provide reliable estimates of their emissions, (ii) demonstrate measurable improvements, and (iii) improve soil health.

Carbon footprinting is an important component of any sustainability initiative, and crops produced with a low carbon footprint have a competitive advantage in the global marketplace. For field crops—and agri-food products in general—nitrous oxide (N_2O) emissions constitute a key sustainability indicator, and N_2O is an important component of the overall carbon footprint. Nitrous oxide is an important greenhouse gas—well as an ozone depleting gas—that is produced in and emitted from soils as a natural consequence of microbial activities. However, the amount of N_2O being generated has increased dramatically because of human activities—with agricultural activities comprising the largest source of these emissions. Indeed, the latest Canadian national inventory report on greenhouse gas (GHG) sources and sinks (Environment and Climate Change Canada, 2019) attributes approximately 70% (27,000 kt CO2-eq) of total Canadian human-induced N_2O emissions to agricultural activities.

For Saskatchewan, agriculture's share of human-induced N_2O emissions is even greater (ca. 88% in 2015). Agricultural soils are the predominant source of this N_2O—primarily reflecting the large and increasing use of nitrogen fertilizers—and are thus a target for N_2O reduction. However, the responsible use of N fertilizer can reduce the carbon footprint of crop production and drive a reduction in N_2O emissions from the agriculture sector. For example, in canola production alone—which since 2012 has exceeded 8.4 million hectares—it is estimated that adopting improved nitrogen management strategies (e.g., 4R nutrient stewardship) can reduce GHG emissions by 1 to 2 million tonnes (Canola Council of Canada, 2019). One means of achieving these reductions is through the use of enhanced efficiency nitrogen fertilizer (EENF) products. In Saskatchewan, as well as across Prairie Canada, the decision to adopt EENF technologies is a consequence of producers actively choosing to utilize premium EENF products (e.g., ESN®, SuperU™ or eNtrench™) in place of lower cost conventional fertilizers (primarily urea or anhydrous ammonia). In general, however, the higher price of EENF technologies relative to conventional fertilizers has prevented their widespread adoption by broad acre grain and oilseed producers. Today, with the cost of synthetic nitrogen fertilizer increasing and the emergence of lower cost EENF technologies, producers are increasingly looking towards technologies that can protect their fertilizer investment while improving both their agronomic and environmental performance. Our previous research has shown that substantial reductions in N_2O emissions are achievable by combining EENFs with more advanced, 4R-based N management practices; i.e., practices that involve applying N fertilizer using the Right source at the Right rate, Right time, and with the Right placement. Indeed, field trials in Saskatchewan—together with companion trials in Manitoba and Alberta—have demonstrated that these products can yield substantial N_2O emission reductions. At the same time, however, poor yields during the first year of the study and no yield (due to severe hail damage) in the second year made it difficult to draw conclusions regarding any potential agronomic benefit associated with the EENFs.

As farms increase in size, time management becomes more important, and as a result, many producers shift their fertilizer application to the fall when prices are generally lower, and time is not at a premium. Although fall fertilizer applications can lead to improved efficiencies during seeding in the spring, the practice remains controversial, with results that can vary widely—depending on environmental conditions after application—and often leads to increased N_2O emissions during the following spring thaw. In general, fall fertilizer applications are not considered a fertilizer best management practice nor an accepted practice under the Nitrous oxide Emissions Reduction Protocol (NERP).

7. Objectives and progress towards meeting each objective

The logistics and time commitment associated with the field component of the study combined with restrictions put in place in response to the coronavirus pandemic meant that the project encountered an unavoidable delay. Nevertheless, all phases of the project (i.e., field and laboratory experiments) have now been completed. The overall objective of the project was to *quantify the influence of enhanced efficiency nitrogen fertilizers on crop nitrogen use efficiency, yield and N_2O emissions*. The specific objectives are listed in the following table:

Objectives (list original/revised objectives)	Status
Quantify and compare crop N uptake, nitrogen use efficiency, yield, and oil content[1] of canola following fall and spring applications of urea, urea treated with a nitrification inhibitor (eNtrench™), and urea treated with dual inhibitors (urease and nitrification inhibitors: SuperU™)	Completed
Quantify and compare N_2O emissions from fall *vs*. spring applications of urea, urea treated with a nitrification inhibitor (eNtrench™), and urea treated with dual inhibitors (urease and nitrification inhibitors: SuperU™)	Completed
Calculate yield-scaled N_2O emission factors for each fertilizer type and application timing to determine the combination that optimizes the balance between agronomic and environmental outcomes (i.e., maximizes yield and N_2O emissions reductions)	Completed

[1] Oil content analyses were not completed during the study. Oil content analyses were to have been performed at the Saskatchewan Structural Sciences Centre (SSSC); however, restrictions in place due to the pandemic prevented us from accessing the facility in 2020 to conduct the analyses. In 2021, the extreme drought resulted in very low yields and there was not enough seed to conduct all the tests required; consequently and given that there had been no oil content measurements in 2020, it was decided to eliminate this from the study.

8. Methodology

Plot Establishment: The study was conducted at the University of Saskatchewan's North Management Area (52°09'17.7"N, 106°36'44.9"W). Soils at the site are classified as Dark Brown Chernozems of the Asquith association and are moderately alkaline (pH = 8.0 ± 0.3) and non-saline (EC = 0.3 ± 0.1 dS m^{-1}), with a loam to sandy loam texture and an organic matter content of 3.9 ± 0.4%. In spring 2019, prior to plot establishment, the site was seeded to barley as part of the normal crop rotation. In fall 2019, research plots (3-m × 10-m) were set-up using a randomized complete block design (RCBD), with fertilizer type (granular urea, urea + eNtrench™, and SuperU™), N rate (soil test recommendation [STR] and 0.7×STR), and timing (fall *vs*. spring application) as the main effects—with each treatment combination replicated four times (see Appendix Fig. A1). Following the barley harvest, fall soil samples (0–15, 15–30, and 30–60 cm; one composite sample for each depth increment from each block/rep) were collected and sent to a commercial soil testing laboratory (*FarmersEdge*; Winnipeg, MB) for analysis and to obtain fertilizer recommendations for the 2020 canola crop. The soil test results indicated that soil N levels were generally "marginal", with *ca*. 36 kg N ha^{-1} in the surface (0–15 cm) and 30 kg N ha^{-1} in the subsurface (15–60 cm) soils. Based on the soil test results—and a target canola yield of 30 bu per acre (1.68 Mg ha^{-1})—the soil test recommendation was 50 kg N ha^{-1}. For the enhanced efficiency products (eNtrench™ and SuperU™) manufacturer recommendations were for application rates approximately 30% below the STR (i.e., a reduction of 15 kg N ha^{-1}) to yield an application rate of 35 kg N ha^{-1}. To evaluate the N-product × rate interaction effect on N_2O emission reductions, however, all fertilizer products were applied at both the STR and 0.7×STR. In addition to the fertilizer treatments, the study included a non-fertilized check plot that was used to quantify background emissions and calculate fertilizer-induced emissions—yielding a total of 13 treatments (Table 1). The EENF products and conventional granular urea (46-0-0) were broadcast by hand in the late fall—after soil temperatures had fallen below 7°C for five consecutive days (Oct 30, 2019)—or at planting the following spring (May 28, 2020). The fertilizer was incorporated into the soil to a depth of about 10 cm immediately after surface application.

Table 1. Fertilizer treatments applied in Fall 2019 and Spring 2020.

Trt. No.	N source [a, b]	Timing	Rate [c]	Plot No. [d]
1	Urea	Fall	STR	112, 206, 302, 410
2	Urea	Fall	0.7×STR	110, 209, 308, 406
3	SuperU™	Fall	STR	105, 211, 311, 413
4	SuperU™	Fall	0.7×STR	113, 203, 301, 403
5	eNtrench™	Fall	STR	101, 208, 303, 408
6	eNtrench™	Fall	0.7×STR	106, 212, 307, 411
7	Non-fertilized check	n/a	0N	111, 201, 312, 404
8	Urea	Spring	STR	107, 204, 304, 401
9	Urea	Spring	0.7×STR	102, 210, 309, 407
10	SuperU™	Spring	STR	109, 213, 310, 412
11	SuperU™	Spring	0.7×STR	108, 202, 305, 405
12	eNtrench™	Spring	STR	103, 205, 313, 409
13	eNtrench™	Spring	0.7×STR	104, 207, 306, 402

[a] SuperU™ is a stabilized N product incorporating both a urease and a nitrification inhibitor (Koch Agronomic Services).

[b] eNtrench is a stabilized N product incorporating a nitrification inhibitor only (Corteva Agriscience).

[c] STR = soil test recommendation (50 kg N ha^{-1}) for conventional urea; 0.7×STR (35 kg N ha^{-1}) = recommended rate for the enhanced efficiency N products.

[d] Refers to the plot diagram in Fig. A1.

In fall 2020, a second set of experimental plots was established in an area adjacent to the YEAR 1 plots (52°09'21.1"N, 106°36'45.2"W) that had also been cropped to barley prior to plot establishment. In YEAR 2 a second non-fertilized control was added (see Appendix Fig. A2 and Table A1), with one set of the 0N plots being tilled in the fall and the second set being tilled in the spring. Fall soil sampling was conducted post-harvest, with the samples sent to a commercial soil testing laboratory (*AgVise*; Benson, ND) for analysis and to obtain fertilizer recommendations for the 2021 canola crop. The soil test results indicated that soil N levels were generally "marginal", with *ca*. 30 kg N ha^{-1} in the surface (0–15 cm) and 22 kg N ha^{-1} in the subsurface (15–60 cm) soils. Based on the soil test results—and a target canola yield of 40 bu per acre (2.24 Mg ha^{-1})—the soil test recommendation was 99 kg N ha^{-1}, with a reduced rate for the EENF products of 69 kg N ha^{-1}. As in fall 2019, the N products were broadcast by hand after the soil temperatures had fallen below 7°C for five consecutive days (Oct 16, 2020). In fall 2020, however, the soil was tilled prior to fertilizer application to provide better control over the distribution of the fertilizer. Nonetheless, the level of soil disturbance remained similar in both years.

Canola production: In YEAR 1 the plots were seeded with hybrid canola Helix Vibrance 6074 RR (Brett Young; MB) on May 28, 2020, and in YEAR 2 with hybrid canola InVigor L345PC (BASF; Mississauga, ON) on May 27, 2021. In both years, the desired plant density was 150 plants m^{-2} with the between-row spacing of 23 cm. To accommodate gas sampling, seedlings within the chamber bases were removed 10 d after planting and the same number of plants manually reseeded along the outer edge of the chamber bases to achieve the same plant density. Germination counts were performed in all plots, and in the case of poor germination were re-seeded as needed (i.e., to fill any gap larger than 20 cm within a plant row). A seeder malfunction in YEAR 1, however, resulted in the plant stands generally exceeding the target and were thinned as necessary between June 18th and June 25th. After thinning, the average number of plants per linear meter (26 $\pm$ 3 plants m^{-1}) was obtained from two random 1-m length rows at the centre of the plots.

For weed control, the alleyways between both the plots and blocks were seeded with canola, which allowed us to successfully manage weeds without the use of herbicide on the site in YEAR 1. The fields were scouted three times weekly for disease, pest, and wildlife damage. Prior to the flowering stage, the cotyledon and young foliage exhibited minor damage (less than 1%) due to flea beetles. Later, with the onset of anthesis, we observed crop damage due to deer grazing the site at night. Despite the use of a variety of management strategies to exclude deer from the site—including the use of a scarecrow, decoy coyote, AM/FM radio, and fencing—there was significant damage to several plots. The intensity of deer damage was visually inspected and evaluated by estimating the degree of inflorescence loss and the location of damaged areas within each plot. During the latter stages of the growing season, we observed a significant increase in the population of grasshoppers and thus to prevent further loss of yield, the crop was terminated with desiccant for early harvest.

In YEAR 2, an electric fence was installed immediately after seeding, which effectively eliminated any wildlife damage. Weed control in Year 2 was achieved by spraying the site with the herbicide Liberty® (glufosinate ammonium; BASF; Mississauga, ON) at the recommended rate of 3.33 L ha^{-1} on June 22, 2021.

Aboveground plant biomass samples were collected from the center of each plot in two 1-m linear rows on August 19, 2020, and August 19, 2021. Plant sampling in Year 1 was restricted to areas where damage due to the deer was least noticeable. In Year 2, sampling was more straightforward as the plots were more uniform and samples were collected from representative areas.

During the 2021 growing season, dry conditions with limited rainfall and frequent extreme heat events severely affected crop growth and yield production. The crop first showed signs of water stress during the second week of June with the leaves wilting and gradually curling, turning yellow, and dropping in the weeks that followed. The canola entered the reproductive stage at the end of June with short flower racemes. Drought conditions continued throughout the growing season to harvest, which resulted in more than half of the field experiencing total crop failure. Missing pods were common on the raceme at harvest and most of the surviving pods were empty or contained only a few very small seeds. As a consequence, the harvested seed was insufficient for the plant tissue %C and %N analysis. Thus, additional plant samples were collected on August 26, 2021, and the composite samples used for analysis. The total area sampled for plant biomass was 3 m^2. Late season precipitation in September resulted in some regrowth of the harvested plants—with new shoots developing from the root system. Although these plants produced no additional seed yield, all regrowth within the 3-m^2

harvest area of each plot was collected on October 21, 2021, and the plant materials analyzed for %N to account for total plant N uptake.

The plant biomass was separated into residue and pods. Fresh and dry weights of the residue and pod samples were recorded before and after being dried to constant weight in an oven at 60°C. Dried canola pod samples were manually threshed and cleaned of chaff using a column seed blower. Plant residue samples were passed through a Wiley mill with a 1-mm mesh sieve. Yield samples were finely ground using a coffee grinder. Between samples, the Wiley mill and coffee grinder were cleaned with compressed air. Ground plant materials were stored in polypropylene vials until analyzed for C and N using a LECO CN628 elemental analyzer (LECO corporation, Michigan, USA).

Gas Sampling: Gas sampling chambers were constructed using rectangular (55.6 cm × 35.6 cm × 13.3 cm; l×w×h) stainless steel "steam pans" equipped with a flange around the edges (Russell Hendrix., Saskatoon, Canada). The chamber lids were retrofitted with a gas sampling port located at the center of the pan and a closed-cell EPDM (ethylene propylene diene monomer) sponge rubber seal attached to the underside of the flange to provide an air-tight seal with the chamber base. Bases for the chambers were constructed using two 65.68 cm × 7.62 cm (l × w) strips and two 38.98 cm × 7.62 cm (l × w) strips of 304-stainless steel formed into an L-shape and welded to form a rectangular frame (73.3 cm × 46.6 cm; l×w) (Outlaw Metal Fabrication, Saskatoon, Canada). During sampling, an adequate seal between the chamber and the base is made by placing a brick on top of the lid to compress the EPDM seal.

The base frames were installed in the research plots immediately following the fall fertilizer application and were left in place over winter to facilitate sampling at the start of the spring thaw. Because of an early freeze, however, GHG samples were not collected in fall 2019. Gas sampling was restarted in spring 2020 and continued throughout the growing season and fall—terminating at soil freeze-up. Soil-derived greenhouse gas (N_2O, CO_2 & CH_4) fluxes were measured by following standard protocols for manually sampled non-steady state vented chambers (Parkin and Venterea, 2010; David et al., 2018) with headspace samples collected 14-min after the chambers were sealed in place and ambient air samples collected (n = 12) for the time-zero measurement. The gas samples were injected into pre-evacuated Exetainer vials (Labco limited, UK) and returned to the *Prairie Environmental Agronomy Research Laboratory* in the Dept. of Soil Science where they were analyzed for N_2O, CH_4, and CO_2 using standard gas chromatography techniques (Farrell & Elliott, 2008) and a Bruker 450 GC (Bruker Biosciences, Billerica, MA) equipped with a ^{63}Ni electron capture detector (N_2O), flame ionization detector (CH_4), and thermal conductivity detector (CO_2).

To help capture the high spatial variability of gas fluxes (especially N_2O), chambers were constructed with a large footprint (*ca*. 2000 cm^2). Each chamber was sampled 35–45 times per year with seasonality and day-to-day variations addressed by increasing sampling frequency during periods when fluxes were expected to be greatest and most variable. For example, the highest sampling frequency (2–3 times per week) occurred at the start of the season during spring thaw and following spring fertilizer/seeding operations. Sampling frequency was then decreased from twice per week to once per week as the growing season progressed and emission intensity decreased, and then to once every two weeks during the post-harvest period to soil freeze-up in the fall. In addition, gas fluxes were measured 24 h after any significant (>6 mm) precipitation event during the sampling season. Data from the manually sampled chambers was then used to calculate total cumulative N_2O emissions, which together with the yield data were used to calculate greenhouse gas emissions intensities (i.e., yield scaled N_2O emissions).

In addition, an automated GHG sampling and analysis system consisting of a Fourier Transform Infrared (FTIR) gas analyzer (Model DX-4015, Gasmet Technologies Oy, Vantaa, Finland), a multiplexer (LI-8150, LI-COR Biosciences, Nebraska, USA), and a series of automated flux measurement chambers (LI-8100, LI-COR Biosciences, Nebraska, USA) were employed to monitor real-time fluxes. Together with the climate data, these real-time measurements were used to adjust gas sampling frequencies as necessary.

Soil moisture levels were monitored three times per week using a Soil Moisture Sensor SM150T HH2 moisture meter (Delta-T Devices Ltd.; Cambridge, UK).

Soil N Availability: Plant root simulator (PRS™) probes (Western Ag Innovations; Saskatoon, SK) were used to monitor NO_3^- and NH_4^+ availability in the soil. The PRS™ probes were installed at different stages of crop development during the 2020 growing season: after seeding (May 29 to June 12), at the early seedling stage (June 12 to June 26), at flowering (July

16 to July 30), and prior to harvest (August 12 to August 24). Early retrieval of the last set of PRS™ probes was necessary to avoid damaging the probes when the plots were combined. For each plot (i.e., each treatment combination), three pairs of anion and cation probes were vertically inserted and tightly packed into 14-cm deep slots in the soil to ensure good soil-to-membrane contact. The PRS™ probes were installed between plant rows *ca*. 0.6 m in from the west edge of the plots and at a 2.5-m interval along the north-south axis of the plots. The anion and cation probes in each pair were installed approximately 15 cm apart and were left in the soil for 14 d at which time they were removed from the soil, thoroughly washed with deionized water in the field, and returned to the lab. Any soil remaining on the resin membranes, plastic cases, or in the gaps between the membrane and plastic case was then removed by further washing. The clean PRS™ probes from each plot were then stored in a zip-lock bag and kept in a cool, moist, and dark environment until they were returned to Western Ag Innovations for extraction and analysis.

In-season plant tissue-N was assessed weekly starting at flowering (July 15th) and continuing until all leaves had senesced (August 3rd). Tissue-N was measured using a Soil-Plant Analysis Development (SPAD) 502 Plus Chlorophyll Meter (Spectrum Technologies, Inc.; Aurora, IL). For each plot, two plants in the centre rows were randomly selected and a SPAD measurement made on the fourth uppermost, fully mature leaf on the main stem of each plant, approximately one-third the distance from the leaf apex. The readings for each plot were recorded and used to calculate an average.

9. Results and Discussion:

The western Canadian Prairies experienced severe drought in both 2020 and 2021, with 2020 being the 9th driest year on record and 2021 being the 2nd driest year on record[1], and as a result yields and N_2O emissions were generally much lower than would normally be expected—especially in 2021. Consequently, the yield, N uptake, and N_2O emissions data for the two years were analyzed separately.

Seed Yield: Averaged across treatments, seed yields in 2020 were 30% lower than the target yield and exhibited a significant (P = 0.0229) N source × rate × timing interaction, with no other significant effects detected. Due to the three-way interaction in 2020, the fertilizer source × rate effect was investigated separately for each timing (Fig. 1). There were no treatment differences when fertilizer was applied in the fall, but a different result emerged for the spring N application treatments. For spring N applications, the only yield difference was between the different rates of eNtrench™ fertilizer—where the reduced rate had lower yields than the soil-test rate (Fig. 1). Apart from these differences, yields were similar among all remaining treatments. Overall, only small yield enhancements were observed with the enhanced efficiency N products when they were spring applied *and only* if the crop was not severely impacted by drought conditions.

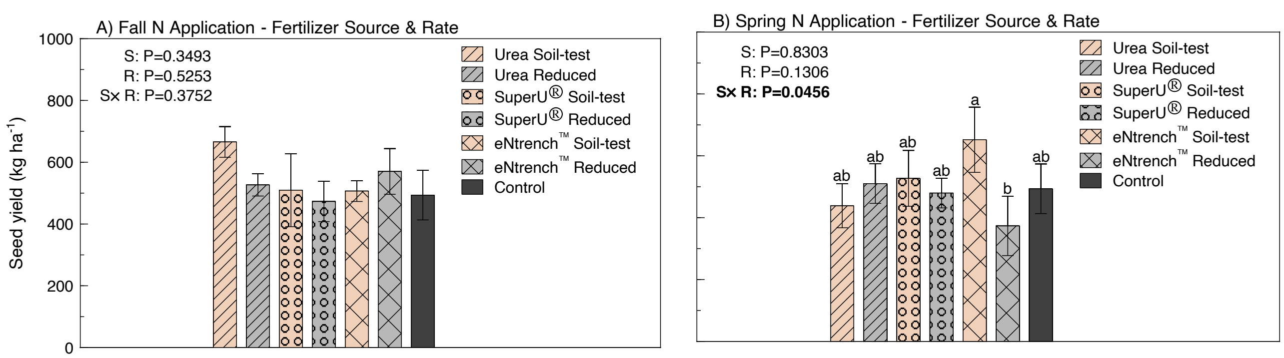

Fig. 1. Seed yield (kg ha^{-1}) for fall N (**A**) and spring N (**B**) applications in 2020, as influenced by fertilizer source × rate. Means followed by different letters show significant different at α = 0.10. Note: there was a three-way interaction of Source × Rate × Timing (P=0.0229). Hence, source and rate were evaluated for each application timing, separately.

[1] Climate records based on data from the Saskatchewan Research Council Climate Reference Station located in the University of Saskatchewan North Management Area (52 09'N, 106 36'W). The station has been monitoring climate variables at this site since 1963 (Wittrock, 2021).

In 2021, only application timing had a significant (P = 0.0404) effect on canola yields, which were severely impacted by drought conditions resulting in very low yields across the board (Fig. 2). Actual seed yields were generally less than 10% of the target yield with no recoverable yield in about one-third of the plots that received fall N applications and about two-thirds of the plots that received spring N applications. Yields were not impacted by fertilizer source or rate, but the timing effect showed that yields were significantly higher when the fertilizer was applied in the fall relative to the spring (Fig. 2). We postulated that this timing effect was a result of better moisture retention in the fall tilled plots compared to the spring-tilled plots. Indeed, the volumetric soil water content (VSWC) in the fall-tilled plots was consistently 20% to 30% greater than that in the spring-tilled plots (data not shown)—with the VSWC decreasing more rapidly in spring-tilled plots as the drought set in.

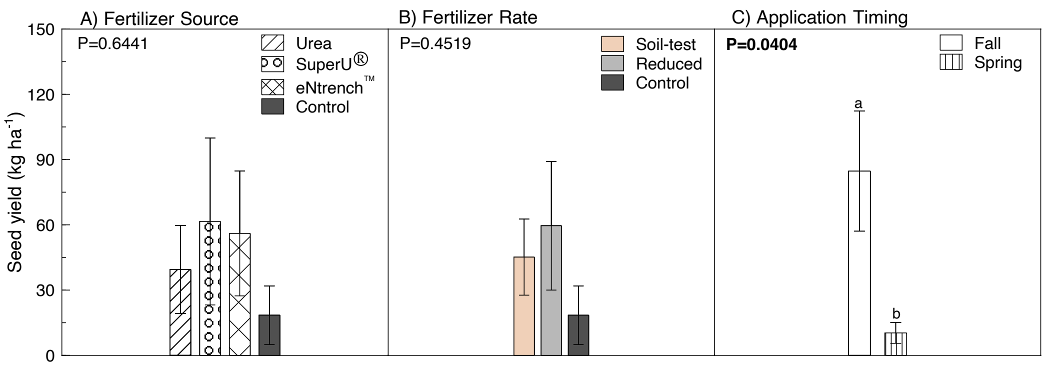

Fig. 2. Seed yield (kg ha^{-1}) in 2021 under the effects of fertilizer source (A), rate (B), and application timing (C). Means followed by different letters show significant different at α = 0.05.

Nitrogen use efficiency: Canola N use efficiency—measured as kg of seed per kg of N fertilizer applied—was independent of fertilizer source in both 2020 and 2021 (Fig. 3). However, applying fertilizer at a reduced rate instead of the soil-test rate improved crop N use efficiency significantly in 2020 and numerically in 2021 (Fig. 2). Only in 2021, when drought severely limited yield production, did the fall N application result in greater crop N use efficiency estimates compared to the spring N application (Fig. 3).

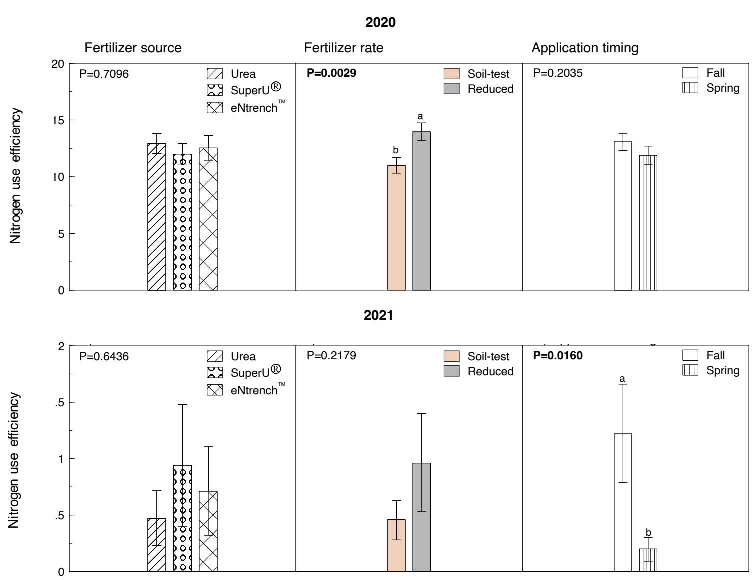

Fig. 3. Nitrogen use efficiency (kg seed kg N^{-1} applied) as influenced by fertilizer source (left), rate (middle) and application timing (right). Means followed by different letters show significant different at α = 0.05.

Nitrous oxide emissions:

Nitrous oxide emissions from soils are well known to be highly variable, both spatially and temporally, and are generally considered to be "event driven" (Yates et al., 2006; Butterbach-Bahl, 2013). Whereas N_2O is produced via nitrification and denitrification, emission events are generally attributed to enhanced denitrification associated with an increase in soil water content and substrate (both N and C) availability. Consequently, in the western Canadian prairies large emission events are generally associated with the application of N fertilizer—especially during rainfall events following a N application—and with snowmelt at the start of the spring thaw. It is important to note that soil microbial communities remain active throughout the year (Drotz et al., 2010; Wertz et al., 2013; Tatti et al. , 2014; Chantigny et al., 2019) and that non-growing season (NGS) emissions are increasingly being recognized as important contributors to total annual N_2O emissions. For example, NGS emissions associated with freeze-thaw events (including the spring thaw) can account for 30% to 90% of total annual emissions (Rochette et al., 2008; Wagner-Riddle et al., 2017; Daly et al., 2022). This is especially true when fertilizer N is applied in the fall. That is, a fertilizer-induced increase in the size of the available N pool coupled with the increase in soil temperature and soil water content that accompanies snowmelt, often results in enhanced denitrification and, in turn, large N_2O emissions.

Daily N_2O emissions during both years of our study followed the typical event-based–background pattern with large emission events coinciding with the spring thaw (regardless of when the N fertilizers were applied) and the spring N fertilizer applications (Fig. 4B and 5B). In general, both intra- and inter-year variability in the daily N_2O emissions were in line with previous investigations conducted in the Canadian prairie region (Dusenbury et al., 2008; Lemke et al., 2018; Thilakarathna et al., 2020)—though the extremely large emissions measured at the start of the spring thaw in 2020 were greater than those normally reported for the region. Previous research has shown that the magnitude of thaw-induced emissions is related to the intensity of the preceding winter; i.e., the number of cumulative freezing degree-days (CFD) during the overwinter period from soil freeze-up to the start of the spring thaw (Wagner-Riddle et al., 2017). And this appears to have been a contributing factor to the inter-annual variability in the spring thaw (ST) emissions observed in our study. For example, the 2019–2020 overwinter period had 623 CFD compared to only 249 CFD during the 2020–2021 overwinter period. As well, antecedent soil moisture (i.e., at soil freeze-up) was greater in the fall of 2019 (VSWC $\approx$ 20%) than in the fall of 2020 (VSWC $\approx$ 9%), which would increase the likelihood of achieving conditions that optimize denitrification during the ST in 2020. By comparison, there also were more than 600 CFD during the overwinter period leading to the 2022 spring thaw; however, following the severe drought in 2021 the soil was depleted of moisture such that the VSWC was <10% prior to the soil freezing. Clearly, it is the combination of factors that controls the magnitude of emissions at spring thaw; for example, a study by Barrat et al. (2021) found that the magnitude of emissions during a thaw event increase as the difference between the dry and wet states of the soil (and hence the WFPS) increases, with emissions increasing exponentially when the soil becomes anaerobic—conditions that likely occurred in spring 2020.

Following the initial burst of N_2O from the thawed soils, N_2O fluxes following the 2019 fall N applications were quite low, despite a series of precipitation events throughout the early growing season (Fig. 4A & 4C). As a result, there was no effect of either N source (i.e., fertilizer type) or N rate on cumulative growing season emissions (Table 2). Conversely, growing season (GS) emissions following the spring N application in 2020 exhibited significant N source (P = 0.0221) and N rate (P = 0.0003) effects, with emissions decreasing in the order: urea > SuperU > urea+eNtrench and 1×STR > 0.7×STR > 0N, respectively. Moreover, GS emissions were generally greater following the spring N applications than the fall N applications, though the difference was significant only for the 2020 GS (see Table 2). Nevertheless, GS emissions during our 2-year study ranged from about 60 to 220 g N ha^{-1} in 2020 and 45 to 300 g N ha^{-1} in 2021, which are considerably lower than those reported other studies in the region. For example, Thilakarathna et al. (2020) reported cumulative GS emissions from fall and spring N applications for spring wheat production in Manitoba in 2016 that ranged from 324 to 537 g N ha^{-1}. Likewise, Lemke et al. (2018) reported cumulative GS emissions from the canola phase of a canola-wheat rotation (2008–2010) in Saskatchewan that ranged from 355 to 539 g N ha^{-1}. The low cumulative GS emissions measured during our study were likely reflective of limited in-season precipitation negatively impacting microbial activity—including the activity of both nitrifier and denitrifier communities.

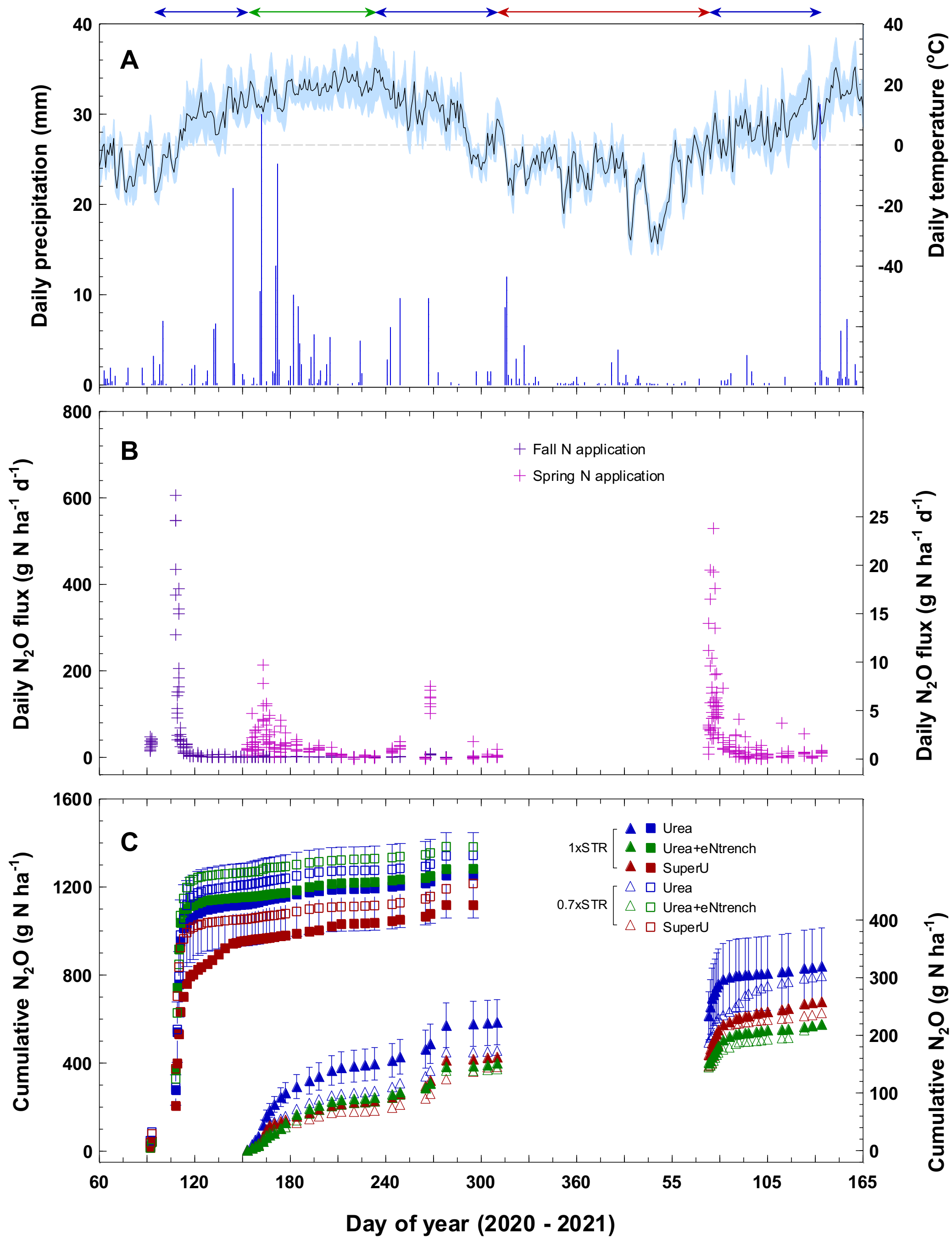

Fig. 4. (A) Daily air temperature and precipitation during the GHG emissions measurement period in 2020 and spring 2021. The solid black line represents the average daily air temperature, and the light blue shaded area represents the range in daily temperature. **(B)** Mean daily N_2O emissions. **(C)** Cumulative N_2O emissions from plots receiving fall (■, □) and spring (▲, △) N applications of urea, SuperU®, or urea+eNtrench™ at the soil test recommendation (1xSTR: 50 kg N ha^{-1}; solid symbols) or 70% of the soil test recommendation (0.7xSTR: 35 kg N ha^{-1}; open symbols). The blue arrows (←→) at the top of the Fig. define the non-growing season, including the spring thaw and post-harvest periods; the green arrow (←→) defines the growing season; and the red arrow (←→) defines the overwinter period. **Note**: daily and cumulative emissions associated with the spring N application are referenced to the y-axis scale on the right. Error bars (i.e., standard error of the mean) are include for the 1xUrea treatment to provide an indication of the variability associated with the cumulative N_2O emission data.

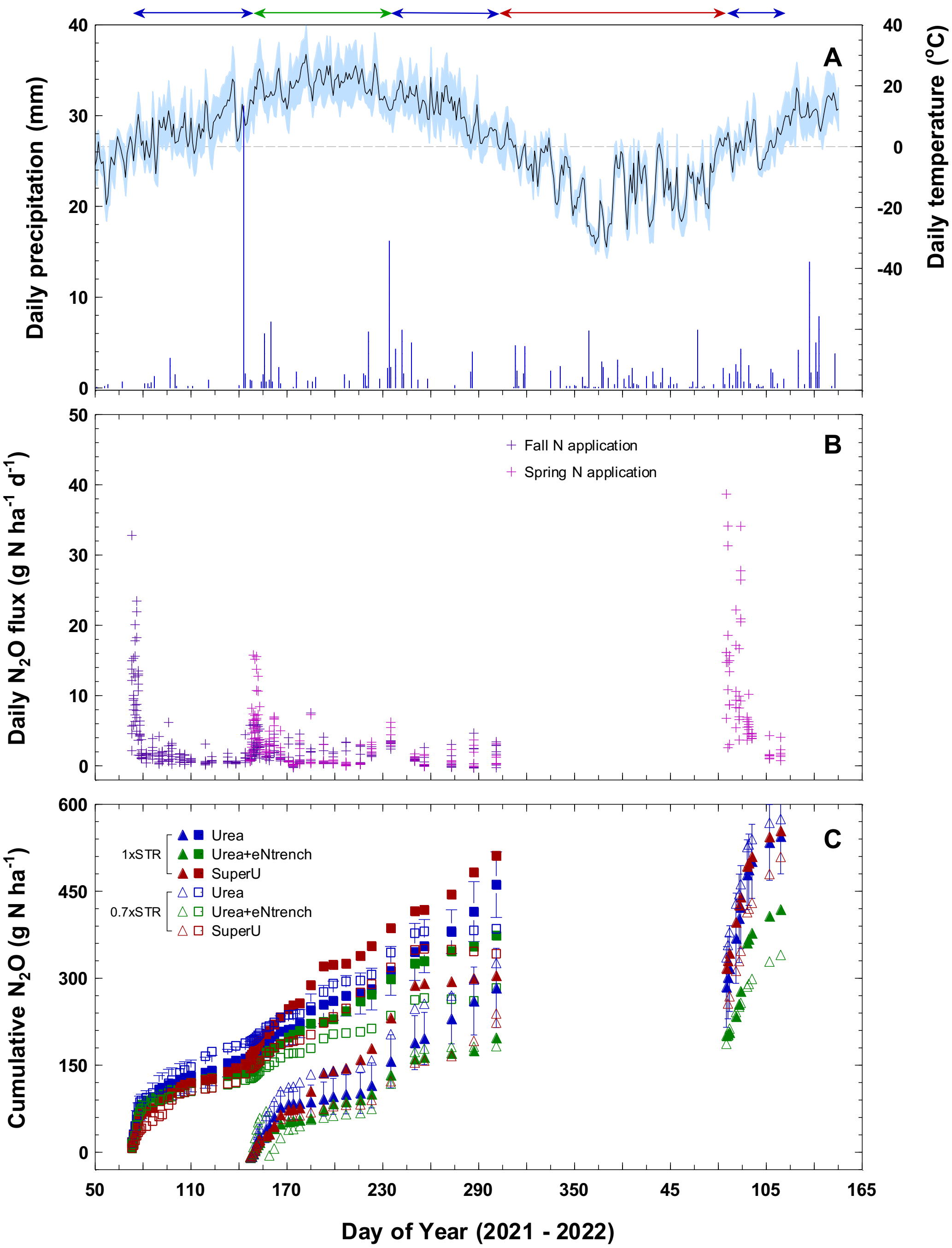

Fig. 5. (A) Daily air temperature and precipitation during the GHG emissions measurement period in 2021 and spring 2022. The solid black line represents the average daily air temperature, and the light blue shaded area represents the range in daily temperature. **(B)** Mean daily N_2O emissions. **(C)** Cumulative N_2O emissions from plots receiving fall (■, □) and spring (▲, △) N applications of urea, SuperU®, or urea+eNtrench™ at the soil test recommendation (1xSTR: 50 kg N ha^{-1}; solid symbols) or 70% of the soil test recommendation (0.7xSTR: 35 kg N ha^{-1}; open symbols). The blue arrows (←→) at the top of the Fig. define the non-growing season, including the spring thaw and post-harvest periods; the green arrow (←→) defines the growing season; and the red arrow (←→) defines the overwinter period. **Note**: error bars (i.e., standard error of the mean) are include for the 1xUrea treatment to provide an indication of the variability associated with the cumulative N_2O emission data.

Table 2. Analysis of variance (3-way ANOVA) for cumulative nitrous oxide (N_2O) emissions during the spring thaw (ST: from the start of the snowmelt/thaw to when the daily flux returned to background levels), growing season (GS: seeding to harvest), and non-growing season (NGS: post-thaw to seeding plus post-harvest to soil freeze-up) and for total annual emissions for the 2019–2020 and 2020–2021 seasons.

Source	n	2019 - 2020 ST	2019 - 2020 GS	2019 - 2020 NGS	2019 - 2020 Total	2020 - 2021 ST	2020 - 2021 GS	2020 - 2021 NGS	2020 - 2021 Total
		——— *P-value* [a] ———							
Block	3	0.0032	***0.0001***	***0.0001***	***0.0112***	0.2479	0.0660	***0.0066***	***0.0001***
N Source (S)	2	0.5739	**0.0642**	0.2253	0.4449	0.6249	0.1724	**0.0961**	***0.0108***
N rate (R)	2	***0.0325***	***0.0004***	0.7195	0.1836	0.8394	***0.0347***	**0.0873**	***0.0435***
Application timing (T)	1	***0.0001***	***0.0005***	***0.0394***	***0.0001***	***0.0001***	0.3141	***0.0001***	***0.0014***
S × R	4	0.8003	0.5307	0.5163	0.9336	0.8954	0.2860	0.5946	0.2785
S × T	2	0.3404	0.1909	0.7508	0.6119	0.3419	0.6597	0.9252	0.8026
R × T	2	0.9707	***0.0348***	0.4309	0.2751	0.6741	0.9289	0.1062	0.2483
S × R × T	4	0.8234	0.5906	0.9812	0.9566	0.7703	0.7678	0.9926	0.9562
		Main effect = Source [b] (kg N_2O-N ha^{-1})							
	Urea	NS	96.0 a	NS	NS	NS	NS	143 a	437 a
	SuperU		77.8 ab					127 ab	429 a
	eNtrench		70.8 b					108 b	357 b
		Main effect = Rate [b] (kg N_2O-N ha^{-1})							
	1×STR	211 b	104 a	NS	NS	NS	132 a	144 a	447 a
	0.7×STR	231 ab	82.9 ab				106 ab	125 ab	381 b
	0N	308 a	62.2 b				89.7 b	108 b	390 ab
		Main effect = Timing (kg N_2O-N ha^{-1})							
	Fall	1103 a	64.4 b	118 a	1329 a	66.6 b	NS	157 a	368 b
	Spring	55.1 b	80.9 a	97.2 b	246 b	222 a		99.8 b	448 a

[a] Statistical analyses were performed using log_{10} transformed data and then back-transformed for presentation. Means separation were performed using Tukey's HSD test at the 0.10 level of probability.

[b] There was a significant N-rate by application timing (R × T) interaction for growing season emissions in 2019–2020 that necessitated a re-analysis of the data using a 2-way ANOVA with N source (N) and rate (R) as the main effects for the fall and spring N application timings. The re-analysis found a significant N source (P = 0.0221) and rate (P = 0.0003) effect but only for the spring N application.

Excluding emissions at ST, N_2O emissions during the NGS (i.e., post-thaw to seeding + post-harvest to soil freeze-up) were generally comparable to cumulative emissions during the GS—the lone exception occurring after the fall 2019 N application when NGS emissions were approximately double those during the GS. Regardless, in both 2020 and 2021 there were significant increases in post-harvest NGS emissions (see Figs. 4C & 5C), and in both years this increase coincided with a period of increased precipitation. However, in 2021 crop yields, and hence crop N removal, were exceedingly low (ranging from only 1.0 to 3.6 kg N ha^{-1}) resulting in a large pool of available soil N that intensified the post-harvest emissions. The large pool of available N in the soil at the end of the 2020 season was likely also a contributor to the relatively large N_2O emissions measured at ST in 2022 (see Fig. 5B and 5C). Moreover, both N source and N rate had an effect on NGS emissions in 2020–2021, with cumulative NGS emissions decreasing in the order: urea > SuperU > urea+eNtrench and 1×STR > 0.7×STR > 0N, respectively (see Table 2). The overall distribution of N_2O emissions during the different measurement periods is illustrated in Fig. 6.

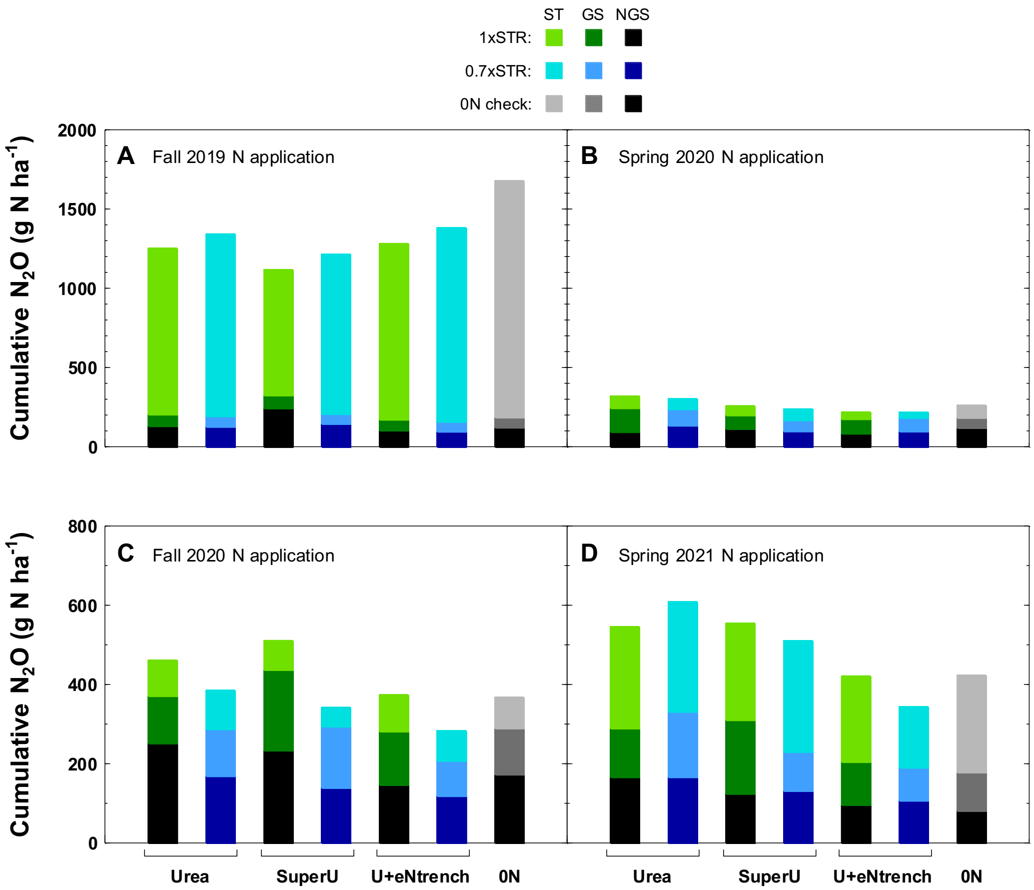

Fig. 6. Annual cumulative N_2O emissions associated with the fall (**A & C**) and spring (**B & D**) N applications. Total annual emissions were grouped according to season: **ST** = spring thaw, defined as the first two weeks following snowmelt and thaw; **GS** = growing season emissions, defined as the period from seeding to harvest; and **NGS** = non-growing season emissions during the late spring (post-thaw to seeding) and fall (post-harvest to soil freeze-up).

Overall, the timing of the N fertilizer applications had the greatest effect on N_2O emissions—impacting emissions during the growing and non-growing seasons, especially at spring thaw. Given the unusually high N_2O emissions at spring thaw in 2020 the data were reanalyzed to remove the effect of the ST emissions by using only the GS + NGS emissions data. This analysis revealed that differences between cumulative emissions associated with the fall and spring N applications were not significant (P = 0.9285). A similar re-analysis of the GS + NGS emissions data for 2020–2021, however, still identified N source (P = 0.0587), N rate (P = 0.0265), and application timing (P = 0.0007) as having an effect on cumulative N_2O emissions—though the results more closely paralleled those for the NGS emissions only in the original analysis (see Table 2). These data provide evidence that emissions triggered by the spring thaw can have a profound effect on total annual emissions and that management options to reduce these emissions should be explored.

Yield-scaled N_2O emissions (YSE) for the study period averaged 1.23 ± 0.38 kg N Mg^{-1} for the fall N application and 0.25 ± 0.13 kg N Mg^{-1} for the spring N application in 2019–2020. These values are somewhat higher than the YSEs reported by Glenn et al. (2021) for no-till canola in Manitoba, which ranged from 0.18 to 0.57 kg N Mg^{-1} in a year with 23% more growing season precipitation than normal (i.e., 2013) and 0.05 to 0.24 kg N Mg^{-1} in a year with 11% less growing season precipitation than normal (i.e., 2015). This likely reflects the combination of higher yields and lower total annual emissions in the Manitoba study. Yield-scaled emissions associated with the fall 2020 and spring 2021 N applications were exceedingly high (ranging from about 300 to 600 g N Mg^{-1}), which reflected the extremely low yields of the 2021 canola crop (see Fig. 2). Our data clearly show that YSEs are extremely susceptible to conditions affecting crop production, should be viewed cautiously when comparing results between studies, and are of little practical value when obtained under extreme weather conditions such as those that occurred in 2021.

Soil N Availability:

Fall application of an EENF can reduce N losses during the spring (Degenhardt et al. 2016), while the spring application of the EENF can slow N release during the first few weeks following fertilization (Trenkel 2010). As such, it was anticipated that fall-applied EENFs would result in higher N supply rates during the seeding stage than the fall-applied urea, and that spring-applied EENFs would lower the N supply rate compared to spring-applied urea. Soil inorganic N (NO_3^- and NH_4^+) supply rates (i.e., availability) monitored during the growing season in 2020 and 2021 revealed that N supply rates were greatest at the begining of the growing season and decreased quickly as the growing season proceeded (Fig. 7)—a trend similar to that observed for N_2O emissions. The largest decrease in soil mineral N levels occurred during the first four weeks after seeding (Fig. 7A and 7B; 7E & 7F), which corresponded to the early growth stage when plant N uptake by canola is greatest (Riar et al., 2020). Plant N uptake continued as crop matured resulting in low soil mineral N availability at the flowering stage (Fig. 7C & 7G). Whereas this trend continued to harvest in 2020 (Fig. 7D), N supply rates increased significantly between the end of flowering and harvest in 2021 (Fig. 7H). The movement of soil inorganic N to plant roots (and the PRS™ probes) is dependent on the soil water content—decreasing under dry conditions and increasing as the soil water content increases in response to precipitation. And in 2021 the site received 22 mm of rain during the final 2-week deployment period, which accounted for the substantial increase in the N supply rates (i.e., N uptake by the PRS™ probes) measured at harvest.

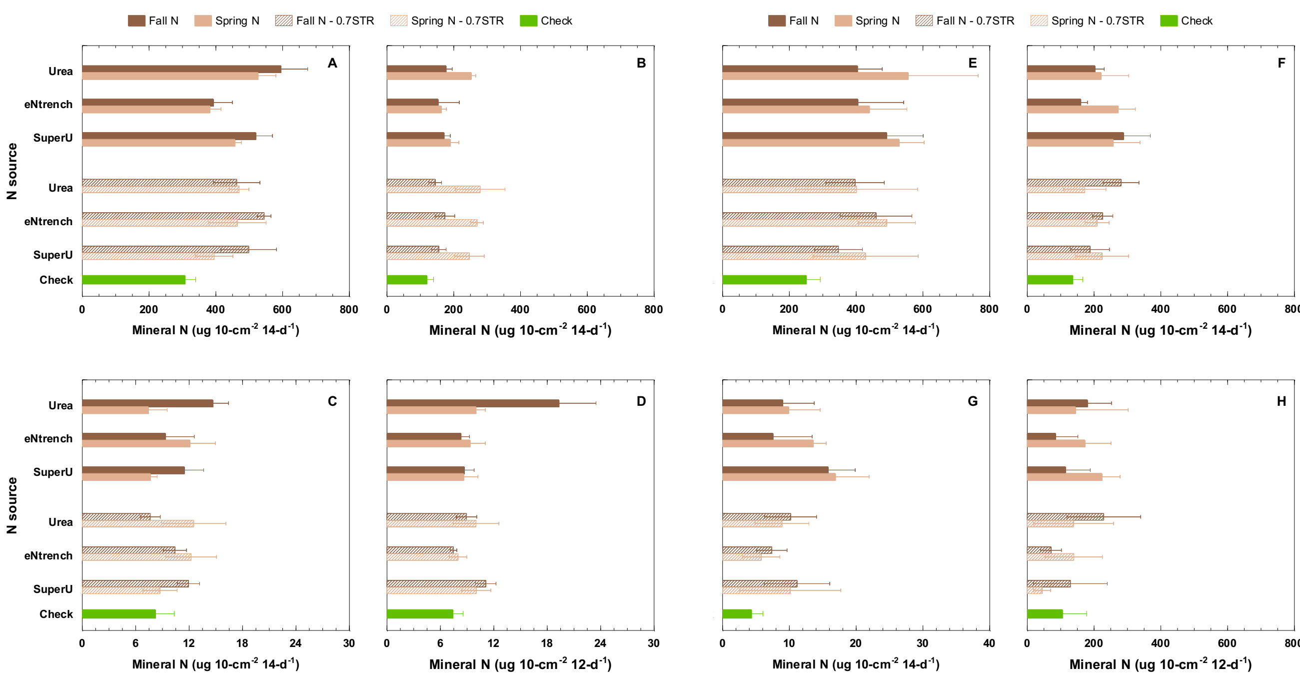

Fig. 7. Soil inorganic N (i.e., $NO_3^- + NH_4^+$) supply rates measured during the growing season in 2020 (panels A–D) and 2021 (panels E–H). Fertilizer treatments included different N sources: conventional urea, SuperU®, and urea + eNtrench™; N rates: soil test N rate (1×STR), reduced N rate (0.7×STR; 70% of the STR), and a non-fertilized (0N) check; and N application timing: fall *vs.* spring. Nitrogen supply rates were measured using plant root simulator (PRS™) probes recovered after 14-d burials at seeding (May 29 to June 12, 2020) (**A** & **E**); during the seedling stage (June 12 to 26, 2020) (**B** & **F**); at flowering (July 16 to 30, 2020) (**C** & **G**), and at harvest (August 12 to 24, 2020) (**D** & **H**). Note: Solid bars represent the average total inorganic N (n=4), and the error bars represent the standard errors.

Given that N uptake by canola increases rapidly during the early growth stages (Canola Council of Canada n.d.; Malhi et al. 2007), these observations were not unexpected. Moreover, plots receiving N fertilizer yielded N supply rates that were larger than those measured in the non-fertilized plots (Fig. 7), though the differences were not significant. As well, though soil inorganic N supply was generally sensitive to N management, there were no consistent trends as indicated by significant N rate × application timing (P = 0.0751), N source × rate × timing (P = 0.0345), and N source × rate (P = 0.0159) interactions at the seedling stage, flowering, and harvest, respectively. A similar tendency was observed during the 2021 growing season where differences in the N supply rates exhibited significant N source × timing (P = 0.0041) and N source × rate (P = 0.0048) interactions at the seedling and flowering stages, respectively. These results are not entirely surprising as it is highly likely that in our study the benefits associated with EENF products were adversely affected by the dry conditions that occurred during the study period, which included one of the driest years on record in 2021 (Wittrock, 2021).

10. Conclusions and Recommendations. *Highlight significant conclusions based on the findings of this project, with emphasis on the project objectives specified above. Provide recommendations for the application and adoption of the project findings.*

The amount and scheduling of fertilizer applications are key controls on the timing and magnitude of N_2O emissions, with fall-applied N believed to be more prone to N losses—particularly as denitrification-induced N_2O emissions when the soil thaws and soil moisture, temperature, and N availability increase. For this reason, fall N applications are thought to be inferior to spring N applications and are generally not considered a sustainable N practice under the Nitrous oxide Emissions Reduction Protocol (NERP). Nevertheless, some canola growers in the Canadian prairies still opt for fall applications due to time and labour management issues. To address sustainability issues, producers are looking to enhanced efficiency N fertilizer (EENF) products to reduce N_2O and protect crop yield. Yet, there is little information regarding the agronomic and environmental performance of EENFs for dryland canola production in western Canada. To address this knowledge gap, we conducted a three-year (two growing seasons) study to evaluate and compare the performance of two stabilized EENF products (SuperU and eNtrench) with that of conventional granular urea—with all products applied in the fall or spring and at the soil test recommendation (STR) or at 70% of the STR.

The western Canadian Prairies experienced drought conditions in 2020, with total annual precipitation totaling only 80% of the 30-year average and growing season precipitation totaling only 67% of the 30-year average. Canola yields in 2020 averaged 1.17 $\pm$ 0.31 Mg ha^{-1} (21 bu ac^{-1}) or about 70% of the target yield. Yields were not affected by either N source or rate following the fall 2019 N applications. Likewise, N source had no effect on yields following the spring 2020 N applications, though there was a small rate effect with the reduced rate (0.7×STR) urea/eNtrench treatment producing yields that were significantly lower than those for urea/eNtrench applied at the STR. Nitrogen use efficiency (NUE) by the 2020 canola crop was not affected by either N source or application timing; however, there was a significant rate effect with higher NUE associated with the reduced N rate.

The 2021 growing season was characterized by severe drought, with total annual precipitation totaling only 48% of the 30-year average and growing season precipitation totaling only 20% of the 30-year average. Consequently, seed yields were generally less than 10% of the target yield with no recoverable yield in about one-third of the plots that received fall N applications and about two-thirds of the plots that received spring N applications. Despite the poor yields there was a significant timing effect with yields being greater when the fertilizer was applied in the fall relative to the spring. This was attributed to better moisture retention in the fall-tilled plots, which had volumetric soil water contents that were consistently 20% to 30% greater than the spring-tilled plots.

Daily N_2O emissions followed a typical event-based–background pattern with major emission events coinciding with snowmelt/spring thaw (ST) and the spring seeding/fertilizer operations. For fall N application, the magnitude of emissions during the spring thaw was determined by environmental and soil conditions both during the overwinter period and at snowmelt/thaw in the early spring. For example, (i) soil moisture leading to the fall soil freeze-up was much greater in 2019 than 2020; (ii) the overwinter period was much more intense in 2019–2020 than in 2020–2021—with more than double the number of cumulative freezing degree-days (CFD); and (iii) the spring thaw occurred more gradually in 2020 than in 2021, resulting in wetter soil conditions during the thaw period. As a result, cumulative ST emissions were much greater in 2020 than in 2021. Moreover, cumulative ST emissions associated with the fall N applications were generally greater than those associated with the spring N applications—reflecting differences in both soil and environmental conditions and available N supply. However, there were no N source or rate effects on the cumulative ST emissions in either year. Growing season (GS) emissions were generally greater following spring N applications than fall N applications, which was to be expected, but the difference was significant only in 2020 when soil moisture was less limiting. Also in 2020, there were significant N source and rate effects on cumulative GS emissions, with the EENFs generating lower emissions than the conventional urea and with emissions decreasing as the N rate increased. In 2021, total annual emissions were dominated by non-growing season (NGS) emissions—especially those occurring in response to late-season rains after harvest. Moreover, during this period the EENF products were more effective at reducing N_2O emissions, though because emissions were quite low throughout the growing season, the differences were also small and significant emissions reductions were achieved only with the urea/eNtrench.

While our study provides new data on the performance of two of common EENF products, results of the study were severely impacted by significant moisture deficiencies in both years and, hence, are not reflective of what producers might expect in a "normal" year. Nevertheless, and with this caveat in mind, our results provide strong evidence that the primary targets for emissions reductions in western Canada should be the controls on emissions occurring at spring thaw and enhanced synchronization of N supply with crop N demand.

11. Is there a need to conduct follow up research? *Detail any further research, development and/or communication needs arising from this project.*

With the cost of synthetic N fertilizer increasing, the possibility of carbon credits, and the emergence of lower cost EENF technologies, producers are increasingly looking towards these technologies as a means of protecting their N fertilizer investment. The drought conditions that persisted throughout the two years of the current study significantly impacted the "value" of the study to producers. For example, whereas there is scientific value to the study (e.g., by knowing how these products perform under drought conditions we can address a gap in the data required to build machine learning tools to model how N management can affect agronomic performance and N_2O emissions reductions), data obtained under more "normal" conditions is required to help producers gauge whether or not these products can provide practical benefits for dryland canola production.

Research is still needed to provide the agricultural industry and growers with information on how EENFs may best balance agronomic and environmental outcomes by improving crop nutrient use efficiencies and reducing N_2O emissions under a range of conditions. Given the logistical and cost considerations imposed by this type of study, however, doing so is not a simple matter. We believe that it should be possible to work with the producer groups responsible for research at the Agri-ARM sites to obtain the quantity and quality of data needed to address this knowledge gap. For example, we propose organizing a GHG sampling school at which we would train personnel from the Agri-ARM sites in the collection of gas samples (i.e., when to and how to collect them). Samples would then be sent to the GHG Analysis Laboratory in the Department of Soil Science at the U of S for analysis.

Future research should also target N management strategies that improve synchronization of N supply with crop N demand, which could include detailed N uptake studies performed under varying soil and environmental conditions. As well, we need to better understand the controls on N_2O emissions at spring thaw; e.g., soil evaporation potential may provide a useful, fine-scale indicator of dryness/drying conditions during the melt, which may be a controlling factor of N_2O production and emission. In recent years, we have begun fielding questions from producers about blending EENFs with conventional N fertilizers to reduce costs while obtaining the benefits of the EENF products. However, there is little information available about whether this approach offers any practical benefits to producers.

12. Patents/ IP generated/ commercialized products:

None.

13. List technology transfer activities:

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Phan, T., Farrell, R.E., Congreves, K.A. 2021. Righting a wrong: can enhanced efficiency products help reduce N_2O emissions from fertilizer? 36th Plant Sciences Graduate Students' Symposium. Mar 5-6, 2021. Oral presentation.

Phan, T., Farrell, R.E., Congreves, K.A. 2021. Righting a wrong: can enhanced efficiency products help reduce N_2O emissions from fertilizer? NSERC CREATE Climate-Smart Connections. Feb 18-19, 2021. Best Student Oral Presentation.

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Phan, T., R.E. Farrell, T. Skoruld, & K.A. Congreves. 2020. Balancing agronomic metrics and nitrous oxide emissions in canola production. *Sustainability of Canadian Agriculture: Farming for Solutions*, Saskatoon, SK, March 12–13, 2020. Poster presentation.

14. List any industry contributions or support received.

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15. Acknowledgements.

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16. Appendices.

16.1 Literature Cited

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16.2 Supplemental Information

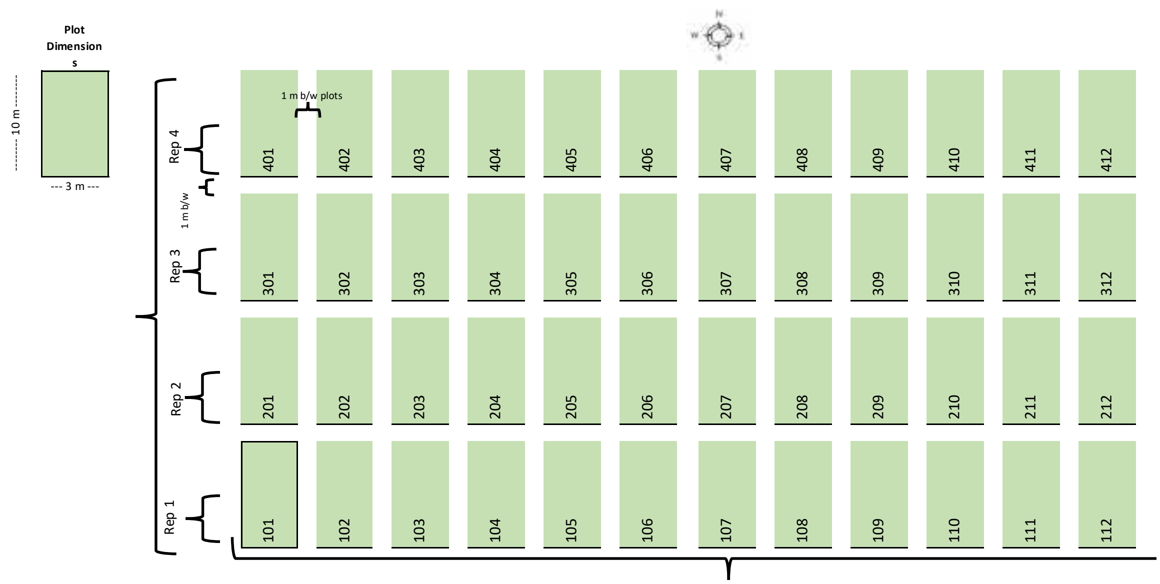

Fig. A1. Plot diagram for the 2019/2020 study at the University of Saskatchewan North Management Area in Saskatoon, SK.

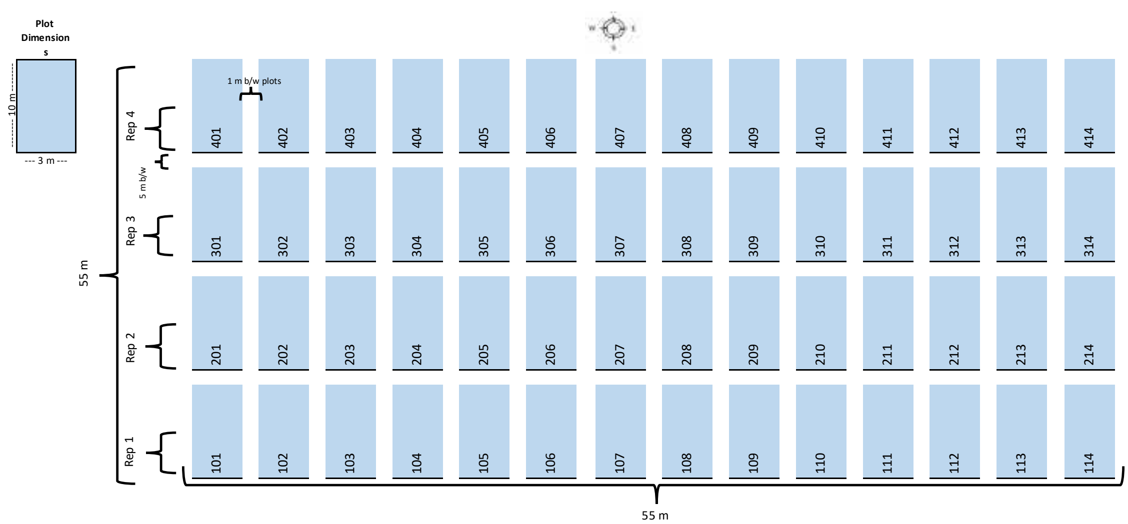

Fig. A2. Plot diagram for the 2020/2021 study at the University of Saskatchewan North Management Area in Saskatoon, SK. Note that for 2020/2021 two sets of check plots (one with fall tillage and one with spring tillage) were included in the experimental design.

Table A1. Fertilizer treatments applied in Fall 2020 and Spring 2021.

Trt. No.	N source [a, b]	Timing	Rate [c]	Plot No. [d]
1	Urea	Fall	STR	112, 211, 307, 406
2	Urea	Fall	0.7×STR	106, 203, 313, 408
3	SuperU™	Fall	STR	108, 206, 310, 412
4	SuperU™	Fall	0.7×STR	114, 213, 303, 401
5	eNtrench™	Fall	STR	104, 208, 302, 411
6	eNtrench™	Fall	0.7×STR	111, 210, 301, 405
7	Non-fertilized check	Fall	0N	101, 214, 305, 407
8	Urea	Spring	STR	103, 212, 308, 410
9	Urea	Spring	0.7×STR	105, 201, 312, 402
10	SuperU™	Spring	STR	110, 207, 314, 403
11	SuperU™	Spring	0.7×STR	113, 205, 304, 144
12	eNtrench™	Spring	STR	102, 204, 306, 409
13	eNtrench™	Spring	0.7×STR	107, 209, 311, 404
14	Non-fertilized check	Spring	0N	109, 202, 309, 413

[a] SuperU™ is a stabilized N product incorporating both a urease and a nitrification inhibitor (Koch Agronomic Services).

[b] eNtrench is a stabilized N product incorporating a nitrification inhibitor only (Corteva Agriscience).

[c] STR = soil test recommendation (50 kg N ha^{-1}) for conventional urea; 0.7×STR (35 kg N ha^{-1}) = recommended rate for the enhanced efficiency N products.

[d] Refers to the plot diagram in Fig. A2.

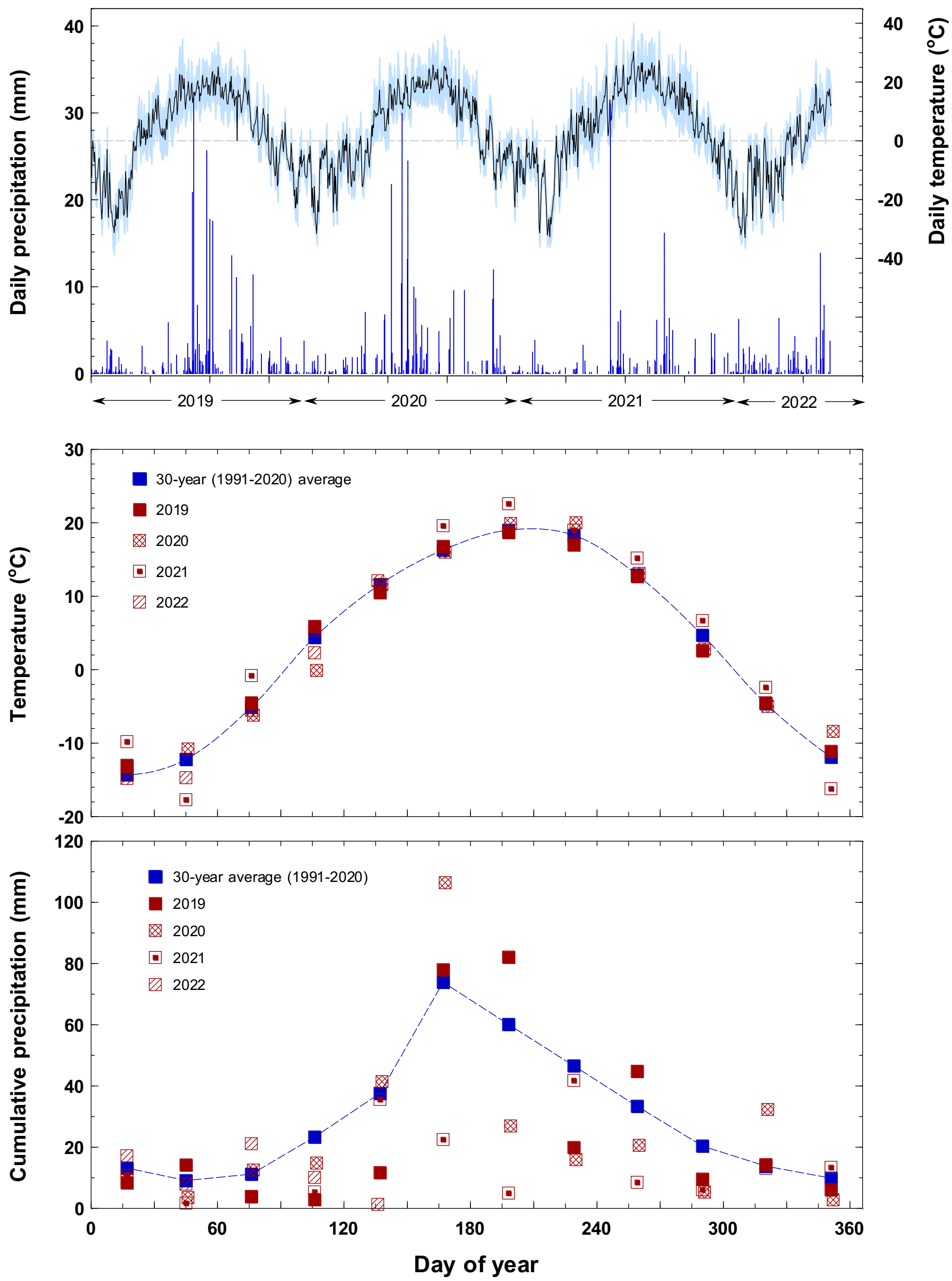

Fig. A3. Climate data obtained from the Saskatchewan Research Council's Climate Reference Station at the University of Saskatchewan North Management Area. **(A)** Daily precipitation (blue vertical bars) and air temperature (the solid black line represents the average daily air temperature; the shaded area represents the range in daily temperatures). **(B)** Average monthly air temperature: the blue squares (■) represent the 30-yr (1991–2020) averages; the red squares (■, ▣, etc.) represent the monthly averages during the study. **(C)** Cumulative annual precipitation (based on monthly averages): the blue squares (■) represent the 30-yr (1991–2020) averages; the red squares (■, ▣, etc.) represent the monthly averages during the study. Note: the data are plotted at the mid-point of each month.

Table A2. Cumulative nitrous oxide (N_2O) emissions from plots receiving conventional and enhanced efficiency nitrogen fertilizers (EENF). The EENFs were SuperU™ (granular urea that incorporates both a urease and nitrification inhibitor) and eNtrench™ (a nitrification inhibitor used to treat urea).

GS Year[a]	N source	N rate (kg N ha^{-1})	Cumulative N_2O emissions (kg N_2O-N ha^{-1})							
			Fall N application				Spring N application			
			ST[b]	GS[c]	NGS[d]	Total	ST[b]	GS[c]	NGS[d]	Total
2020	Check	0	1.494 (0.302)	0.064 (0.004)	0.119 (0.015)	1.678 (0.298)	0.097 (0.036)	0.080 (0.013)	0.246 (0.052)	0.423 (0.040)
	Urea	35	1.152 (0.146)	0.066 (0.006)	0.125 (0.021)	1.344 (0.163)	0.103 (0.016)	0.132 (0.045)	0.068 (0.025)	0.303 (0.080)
		50	1.050 (0.193)	0.074 (0.009)	0.128 (0.021)	1.253 (0.194)	0.151 (0.028)	0.091 (0.017)	0.078 (0.026)	0.320 (0.066)
	SuperU	35	1.010 (0.241)	0.062 (0.008)	0.143 (0.046)	1.216 (0.215)	0.069 (0.008)	0.097 (0.025)	0.073 (0.014)	0.239 (0.040)
		50	0.794 (0.153)	0.081 (0.024)	0.242 (0.132)	1.118 (0.166)	0.086 (0.013)	0.111 (0.022)	0.061 (0.027)	0.258 (0.057)
	Urea/eNtrench	35	1.226 (0.412)	0.062 (0.016)	0.094 (0.010)	1.382 (0.402)	0.085 (0.009)	0.096 (0.021)	0.038 (0.003)	0.218 (0.009)
		50	1.113 (0.194)	0.068 (0.003)	0.101 (0.012)	1.283 (0.199)	0.092 (0.012)	0.081 (0.016)	0.081 (0.016)	0.219 (0.029)
2021	Check	0	0.079 (0.024)	0.117 (0.044)	0.172 (0.048)	0.367 (0.044)	0.097 (0.036)	0.080 (0.013)	0.246 (0.052)	0.423 (0.40)
	Urea	69	0.099 (0.037)	0.118 (0.033)	0.168 (0.022)	0.385 (0.082)	0.165 (0.037)	0.165 (0.070)	0.278 (0.051)	0.575 (0.132)
		99	0.091 (0.024)	0.120 (0.020)	0.251 (0.038)	0.462 (0.057)	0.123 (0.038)	0.166 (0.060)	0.257 (0.059)	0.546 (0.064)
	SuperU	69	0.049 (0.011)	0.155 (0.034)	0.139 (0.022)	0.342 (0.053)	0.098 (0.018)	0.131 (0.034)	0.281 (0.020)	0.511 (0.042)
		99	0.075 (0.025)	0.203 (0.047)	0.233 (0.059)	0.511 (0.110)	0.186 (0.022)	0.124 (0.039)	0.246 (0.073)	0.555 (0.125)
	Urea/eNtrench	69	0.076 (0.019)	0.089 (0.011)	0.118 (0.024)	0.283 (0.022)	0.083 (0.018)	0.106 (0.022)	0.155 (0.036)	0.344 (0.023)
		99	0.093 (0.015)	0.135 (0.026)	0.146 (0.032)	0.374 (0.056)	0.108 (0.026)	0.096 (0.022)	0.218 (0.053)	0.422 (0.097)

[a] GS Year: growing season year. Fall N applications were made in the fall of the previous year (e.g., in October 2019 for the 2020 GS).

[b] ST = spring thaw, defined as the first two weeks following snowmelt and thaw.

[c] GS = growing season, defined as the period from seeding to harvest.

[d] NGS = non-growing season defined as the late spring (post-thaw to seeding) and fall (post-harvest to soil freeze-up).