A Matter of Timing and Source: Enhanced Efficiency Nitrogen Fertilizers and Products to Reduce Nitrous Oxide Emissions from Soils in the Prairie Provinces

Project Report
Submitted by
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Executive Summary

Increasing atmospheric concentrations of greenhouse gases (GHG; CO_2, N_2O, CH_4) is resulting in climate change. Agriculture accounts for 10% of total GHG emissions in Canada with N_2O being the major contributor. Application of synthetic nitrogen (N) fertilizers is the largest source of N_2O emissions, with the prairie provinces of Manitoba, Saskatchewan, and Alberta accounting for 80% of all synthetic fertilizer N used in Canada. The 4R Nutrient Stewardship® framework of using the right source, rate, timing and placement of fertilizer N may be a useful means to reduce N_2O emissions from agricultural soils in the Canadian Prairies. Farmers are faced with practical challenges of applying N fertilizers such as anhydrous ammonia are urea in the fall, though the existing best management practice for this region generally regards fall application as inferior to spring application. It remains unclear if there is an advantage to use enhanced efficiency fertilizers (EEF) such as urea stabilized with nitrification and/or urease inhibitors (SuperU®, eNtrench™, LIMUS®) and anhydrous ammonia stabilized with the nitrification inhibitor N-serve®, and polymer-coated urea (ESN) to control the release rate of N on grain yields and N_2O emissions of spring and fall-applied fertilizer N.

The current project addresses the lack of information regarding the benefit of N EEF products to yield of spring wheat and emissions of N_2O across the Canadian Prairies. In particular, the project examines if EEF products can improve yield and reduce N_2O emissions of fall to that of spring applied N. This report synthesizes results of field studies at 12 site-years across Manitoba (6), Saskatchewan (4), and Alberta (2).

Using replicated plot-based field trials across Manitoba, Saskatchewan, and Alberta, Fall application of N (urea and anhydrous ammonia) increased N_2O emissions for 5 of 12 site-years and reduced emissions for two site-years than Spring application. Fall application of N also had lower wheat yield for four site-years compared to Spring application. At most site-years (9 of 12), there were no interaction effect between N source and application timing on cumulative N_2O emissions, suggesting all EEF products performed similarly irrespective of timing. Similarly, no source by timing interaction effect on yield of spring wheat was observed at all site-years except one in Manitoba, confirming that the effect of EEF products on yield was independent on application timing.

The inclusion of the inhibitor of nitrification, N-serve, with anhydrous ammonia did not affect grain yield or N_2O emissions. However, EEF products of urea significantly reduced cumulative N_2O emissions for 9 of 12 site-years (5 from MB and 4 from SK). In contrast, EEF N products did not affect grain yield except for one site year (St. Adolphe in 2017) where ESN significantly increased yield than urea. The EEF products of urea containing a nitrification inhibitor, SuperU and eNtrench, were most consistent in reducing N_2O emissions compared to urea, regardless if emissions were estimated on an area-, applied N-, or yield-scaled basis. However, the EEF products of urea not containing a nitrification inhibitor, ESN and LIMUS, did not reduce the emission of N_2O compared to urea. For the site years with a significant urea product effect, the mean N_2O emissions for SuperU and eNtrench was about half that of urea.

The two site-years in Alberta did not show a benefit of SuperU or eNtrench to a reduction in N_2O emissions. This was likely due to high variability in N_2O emissions between replicated plots for the sites compared to those in the other Prairie provinces.

These results suggest a high dependence of fertilizer timing effect on environmental factors such as soil and weather conditions. The sites with more precipitation, especially those with greater fall soil moisture and more snow over the winter, are more likely to have greater N_2O emissions from fall than spring-applied fertilizers due to conditions conducive to thaw emissions from denitrification.

The results of this project are particularly important to advise farmers in the use of EEF fertilizer products to affect grain yield of spring wheat and emissions of N_2O. We conclude that 1) Across all site-years, SuperU and eNtrench were the most optimal products to reduce N_2O emissions and maintain productivity; 2) Fall application was inferior to spring application in term of yield production and N_2O reduction. Further studies should investigate whether reduced rates of EEF products can further reduce N_2O emissions while maintaining productivity. A research priority is also to pursure an effective EEF product to reduce N_2O with anhydrous ammonia, especially for that applied in fall.

1. Project Description

1.1 Introduction and Background

The anthropogenic emission of greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) have been identified as a major cause of climate change. In Canada, the agriculture sector contributes approximately 10% of the total national anthropogenic GHG emissions, with N_2O accounting for 72% (Environment Canada, 2017). Nitrous oxide is a gas that has about 265 times more global warming potential than CO_2 in the atmosphere. Increased use of synthetic N fertilizers is a major contributor to rising atmospheric N_2O, and it is therefore important to develop fertilizer management strategies to reduce these emissions from agricultural land. This is particularly important for the Canadian Prairies and Northern Great Plains Region of Manitoba, Saskatchewan, and Alberta because this region accounts for approximately 80% of all synthetic fertilizer N used in Canada (Statistics Canada, 2013).

The 4R Nutrient Stewardship® of using the right fertilizer source, rate, timing, and placement provides a framework to ensure economic, social and environmental goals (Fig.1, IFA 2009). It requires the implementation of best management practices (BMPs) of fertilizer management that optimize the efficiency of fertilizer use. The 4R components need to be considered synergistic due to the interactions of crop, soil and weather factors (Venterea et al., 2016). Therefore, 4R nutrient management practices can further be tailored based upon the crop and environment supporting crop production.

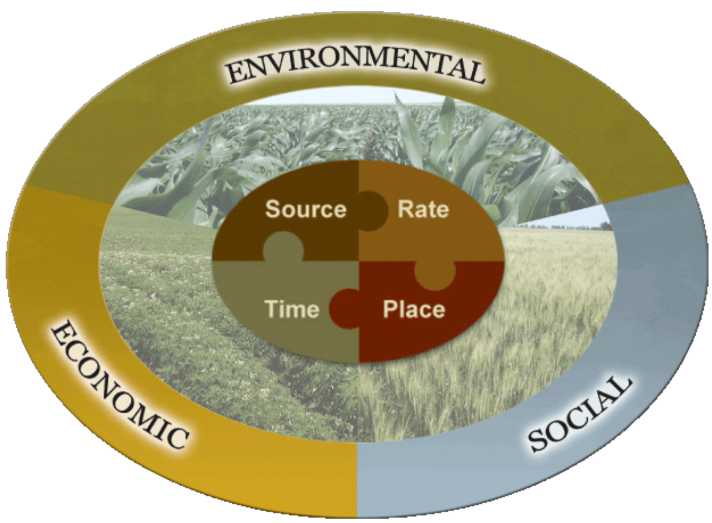

Fig. 1. The basic scientific principles of 4R Nutrient Stewardship

In the Canadian Prairies, anhydrous ammonia or conventional urea are frequently applied in the fall to capitalize on lower fall fertilizer prices, soil conditions that are more conducive to field operations, and available time and labour. Using a flux-gradient micrometeorological approach, we recently showed that late fall application of anhydrous ammonia before soil freeze-up decreased growing season N_2O emissions but increased emissions at thaw compared to spring pre-plant application (Tenuta et al., 2016). Besides, existing 4R best management practices in the prairie provinces generally regard fall fertilizer application as being inferior to spring application, particularly to overall agronomic N use efficiency. Our lab has evaluated the N_2O emission reductions efficacy of a range of commercially available enhanced efficiency N products applied at planting or pre-plant in spring (Asgedom et al. 2014; Gao et al., 2015, 2017). It remains unknown whether applying enhanced efficiency fertilizers in fall can reduce emissions and maintain or increase crop productivity. The effect of N-serve (nitrapyrin) on N_2O emissions from anhydrous ammonia is also not fully researched. Within the context of the 4R Nutrient Stewardship Research Network, this project is designed to resolve significant gaps in understanding the interaction fertilizer N addition timing (fall, spring) and source (enhanced efficiency fertilizers) to increase N use efficiency and reduce loses of the nutrients to the environment.

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1.2 Technology Description

1.2.1 Site description

Plot-based field experiments were established at 12 site-years (six in MB, four in SK, and two in AB) as following:

2015	MB (2)	SK (0)	AB (0)

2016	MB (2)	SK (2)	AB (1)
2017	MB (2)	SK (2)	AB (1)

A summary of treatments is shown in Table 1; each research site was evaluated for fall versus spring application of conventional granular urea (#1) and anhydrous ammonia (AA) (#6) as sources of synthetic nitrogen fertilizer, as well as urea-based enhanced efficiency nitrogen fertilizers including Environmentally Smart Nitrogen (ESN®) – Agrium (#2), SuperU® - Koch Agronomic (#3), eNtrench™ – Dow AgroSciences (#4) and LIMUS®-BASF (#5), alongside a sole NH_3-based enhanced efficiency fertilizer formulation N-Serve® – Dow AgroSciences (#7). These commercially available enhanced efficiency fertilizer formulations utilize nitrification inhibitors (DCD, nitrapyrin), urease inhibitors (NBPT, NPPT) or polymer coatings to modify soil nitrogen dynamics, microbial processes or the release characteristic of nitrogen from fertilizer granules. Each of these products utilizes a specific formulation, combination of active ingredients, or physical properties to prevent reactive nitrogen species such as nitrate (NO_3^-) and ammonium (NH_4^+) losses processes such as ammonia volatilization, denitrification, or leaching. Each site-year also included an unfertilized Control (0 added N) plot.

Table 1. Treatment description in the field trials in Manitoba, Saskatoon and Alberta.

Treatment #	Nitrogen Source	Product	Application Timing
1	Granular	Urea	Fall
2	Granular	ESN®	Fall
3	Granular	SuperU®	Fall
4	Granular	eNtrench™	Fall
5	Granular	LIMUS®	Fall
6	Anhydrous Ammonia	NH_3	Fall
7	Anhydrous Ammonia	N-Serve®	Fall
8		Control	
9	Granular	Urea	Spring
10	Granular	ESN®	Spring
11	Granular	SuperU®	Spring
12	Granular	eNtrench™	Spring
13	Granular	LIMUS®	Spring
14	Anhydrous Ammonia	NH_3	Spring
15	Anhydrous Ammonia	N-Serve®	Spring
16		Control	

1.2.2 Sampling and measurements

Greenhouse Gas Sampling

Gas samplings were conducted for ~ 35-40 sampling days each site-year, using static-vented chambers. Many of the sampling days were concentrated around natural events (e.g. spring thaw) or agronomic operations (e.g., fertilizer application and seeding) that are known to contribute to cumulative seasonal nitrous oxide (N_2O) emissions. A gas sample was collected into a pre-evacuated Exetainer® vial from each chamber every 20 minutes over one hour. Samples were then analyzed for nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) by gas chromatography. Fluxes of greenhouse gases were estimated using the HMR package (Pederson et al. 2010) in R software (Gao et al. 2013). Growing season cumulative N_2O emissions (kg N_2O-N ha^{-1}) for each chamber was estimated by summation of linear interpolation of daily N_2O emissions. Some field activities from Manitoba sites are presented in Fig. 2.

Nitrogen Use Efficiency

Immediately following fall and spring application of nitrogen fertility products, soils were monitored intensively to track overwinter and seasonal changes in the concentration of soil nitrate (NO_3^-) and ammonium (NH_4^+) levels. With continued crop growth and end-of-season yield determinations, soils were again sampled for post-harvest NO_3^- and NH_4^+ levels. Total aboveground biomass and the nitrogen content of straw and grain samples were also determined. These data were used to quantify fertilizer nitrogen use efficiency in addition to the nitrous oxide emission intensity relative to grain yield and biomass generated by conventional and enhanced efficiency nitrogen products.

Agronomic Measurements

Throughout the study indicators of crop performance, including crop emergence, stand counts, canopy heights, days to flowering or maturity were monitored leading up to final determinations of crop yield. Environmental conditions (e.g., soil moisture, rainfall events) known to regulate nitrous oxide emissions from soils and contribute to crop growth and yield potential have also been monitored.

Fig. 2. Field activities in Manitoba field trials.

1.3 Project goals

1) Demonstrate and quantify regional reductions in nitrous oxide (N_2O) emissions achieved through widespread adoption of enhanced efficiency fertilizer (EEF) products across the Prairie Provinces of Alberta, Saskatchewan, and Manitoba
2) Determine N_2O reduction potential of spring versus fall applications of conventional and enhanced efficiency synthetic N fertilizers.
3) Extrapolate N_2O emission reductions, and its CO_2 equivalents (Mg) attained through using EEF technologies in the Prairie Provinces.
4) Determine experimentally-based N_2O emission modifiers for the Nitrous Oxide Emissions Reduction Protocol (NERP) for Alberta and Saskatchewan and enable agricultural producers to earn carbon offsets.
5) Evaluate the agronomic and economic benefits of EEF technologies to the agriculture industry, and identify levels of compensation required for growers to broadly implement EEF technologies.

1.4 Work Scope Overview

This project combines research from prairie provinces and focuses on developing N_2O reduction protocols in term of using source and timing management of nitrogen fertilizer within the 4R Nutrient Stewardship framework. The scope of work includes activities and coordination in fulfillment of the research objectives; development and delivery of research-based and grower accessible factsheets and presentations; and training HQP such as graduate students.

2. Outcome and learnings

2.1 Analysis and Discussion on Results of experiments

2.1.1 Daily N_2O flux

Daily N_2O flux in response to fertilizer timing and sources differed depending on site-years. At MB-Warren (Fig. 3), fall application of fertilizers generally did not induce appreciable flux peaks immediately following application. Instead, emission peaks occurred on 2015-May-27 in plots which received fertilizer application in fall. The maximum flux rate was recorded in the LIMUS treatment, followed by AA, ESN, Urea, SuperU, AA+N-serve treatments. Interestingly, emission peaks with spring applied N treatments were comparable or even lower than those with a Fall application, except AA+N-serve applied in spring which had a higher emission peak than that applied in fall. Spring application induced two emission peaks (May-27 and June-10) within six weeks after the application. Emission peaks were generally lower in the SuperU and eNtrench than other treatments. The unfertilized control plot had the lowest flux for both fall and spring applications.

Similar results were found at MB-Glenlea (Fig. 4). Fall application of fertilizers generally did not induce appreciable flux peaks following application. The AA and AA+N-serve treatments resulted in N_2O emissions at soil thaw in early spring with peak flux rates of approximately 35 g N ha^{-1} d^{-1}. The LIMUS treatment had the maximum flux rate of 260 g N ha^{-1} d^{-1} on 2015-May-22, followed by urea (150 g N ha^{-1} d^{-1}). Spring application had lower emission peaks for most fertilizer sources, except AA+N-serve applied in spring had higher emission peak than that applied in fall. For both spring and fall application, SuperU and eNtrench had generally lower emission peaks than other treatments. ESN applied in spring had a delayed emission peak of 65 g N ha^{-1} d^{-1} on 2016-June-25, about five weeks after application.

At MB-Carman, fall application of fertilizers also did not induce appreciable flux peaks immediately following application, whereas appreciable N_2O emissions occurred during soil thawing in early spring (Fig. 5). Fall AA treatments resulted in the highest peak flux rates at both spring-thaw and post-planting periods, being 36 and 87 g ha^{-1} d^{-1}, respectively. For spring application, AA+N-serve, AA, LIMUS, and urea treatments had higher flux rates than other treatments. SuperU, eNtrench, and ESN had lower flux rates. For both spring and fall application, a small emission peak (<30 g N ha^{-1} d^{-1}) also occurred later in the growing season (2016-July-15), likely induced by a rainfall event.

At MB-LaSalle, fall application of fertilizers also did not induce appreciable flux peaks following application and spring-thaw periods (Fig. 6). AA and AA+N-serve induced emission peaks on 2016-May-1 whereas emissions from the other treatments peaked around June-1. Emission peaks from fall applications were generally lower than those from spring application. Similar to other site-years in MB, AA+N-serve had the highest flux rate in the post-planting period, followed by AA, urea and LIMUS treatments. Use of SuperU, eNtrench, and ESN generally reduced emission peaks compared to other treatments.

At MB-St. Adolphe, fall application did not induce appreciable flux peaks following application but increased N_2O flux during spring-thaw (Fig. 7). Emission peaks were highest in eNtrench treatment (272 g N ha^{-1} d^{-1}), followed by ESN (199 g N ha^{-1} d^{-1}) on 2017-March-29.

Interestingly, both spring and fall applications did not induce N_2O emission peaks during the crop growing period.

At MB-Stephenfield, emission peaks were significantly lower compared to those at other site-years in MB. Fall-applied ESN had small emission peaks on 2017-May-15, and other treatments did not induce appreciable flux peaks through the winter, spring-thaw and in spring. Spring application of fertilizers did not increase N_2O emissions compared to the unfertilized control (Fig. 8).

N_2O flux from both fall and spring application treatments were monitored over a full-year period at the SK sites in the 2016 and 2017 crop years. At SK-NIR-2016 (non-irrigated), fall application did not immediately induce N_2O flux peaks but increased N_2O flux during spring-thaw in early spring (Fig. 9). Emission peaks were highest in ESN treatment, followed by LIMUS, AA, and urea, whereas SuperU and eNtrench had lower N_2O flux peaks than other treatments. No emission peaks were observed in the crop growing period for fall application treatments. In contrast, spring application of fertilizers significantly increased N_2O emissions within one week following application, with maximum flux peak from urea (66 g N ha^{-1} d^{-1} on 2016 May 26), followed by AA+N-serve and AA treatments. Other treatments had no obvious emission peaks, with N_2O flux rates generally lower than 10 g N ha^{-1} d^{-1}. In early spring 2017, LIMUS and urea treatments induced N_2O flux peaks approximately at 20 g N ha^{-1} d^{-1} whereas other treatments did not.

Similar to its non-irrigated counterpart, fall application at the SK-IR-2016 (irrigated) site did not induce immediate N_2O flux peaks but did show an N_2O flux during spring-thaw (Fig. 10). Emission peaks were highest in LIMUS, followed by AA, urea and AA+N-serve. No emission peaks were observed in the crop growing period for the fall application treatment. In contrast, spring fertilizer application significantly increased N_2O emissions within one week following application, with flux peaks being highest for urea and AA treatments. ESN induced a delayed and small emission peak of approximately 40 g N ha^{-1} d^{-1} on 2016-June-28. Spring application treatment did not induce appreciable N_2O emissions in early spring 2017. The irrigated site had generally higher emission peaks for all treatments compared to the non-irrigated site.

At SK-NIR-2017 site (non-irrigated, Fig. 11), again fall application did not induce significant flux events in fall, but there were several small emission events in spring 2017. The maximum flux peak (20 g N ha^{-1} d^{-1}) was observed in AA+N-serve treatment on 2017-May-7. ESN resulted in two small peaks (15 and 18 g N ha^{-1} d^{-1}) on 2017-May-23 and 2017-June-21, respectively. Spring application of ESN and LIMUS treatments resulted in emission peaks, with the maximum N_2O flux rate of 30 g N ha^{-1} d^{-1} coming from ESN on 2017-June-21. Also, 2017 spring application resulted in spring-thaw N_2O emissions in April 2018, with the highest flux rate of 63 g N ha^{-1} d^{-1} occurred with AA+N-serve, followed by LIMUS, SuperU, and urea.

At SK-IR-2017 site (irrigated, Fig. 12), there were no post-application N_2O flux peaks in fall, but increased N_2O flux did occur in early spring (Fig. 8). Emission peaks were highest in fall-applied LIMUS (75 g N ha^{-1} d^{-1}), followed by AA+N-serve and urea. The eNtrench treatment had lower N_2O flux peaks than others. SuperU did not induce an emission peak in early spring but did induce a small emission event on 2017-July-10, with a flux rate of 33 g N ha^{-1} d^{-1}. Spring-applied Urea and ESN induced N_2O emission peaks on 2017-June-2 and 2017-July-9, with flux rates at 55 and 64 g N ha^{-1} d^{-1}, respectively. The maximum N_2O flux peak in spring of 2018 was 123 g N ha^{-1} d^{-1}

from LIMUS, followed by ESN, AA, SuperU and AA+N-serve treatments. Similar to 2016, the irrigated site had generally higher emission peaks for all treatments than the non-irrigated site.

At AB-2016 site (Fig. 13), N_2O flux peaks did occur immediately following fall application but did occur during the spring thaw. All treatments had similar peak flux rates at approximately 25 g N ha^{-1} d^{-1}. Fall application also resulted in emission peaks on 2016-May-25 with flux rate following the order of eNtrench > urea > AA+N-serve = AA. Treatments of ESN, SuperU, and LIMUS had comparable flux rates as the control. Spring application increased N_2O emissions following application, with emission peaks also on 2016-May-25. The AA treatment had the maximum flux rate of 102 g ha^{-1} d^{-1}, followed by SuperU, eNtrench, urea and AA+N-serve treatments. The ESN and LIMUS treatments had the lowest flux rates.

At AB-2017 site (Fig. 14), fall application did not induce N_2O flux peaks in fall but did induce N_2O emission events in early spring. The first event occurred on 2017-April-6 with emission peaks followed order of AA+N-serve > LIMUS > SuperU = eNtrench > urea = ESN > AA > control. The second event occurred on 2017-May-3 with emission peaks being greater in urea, SuperU, LIMUS, and ESN, than AA and AA+N-serve treatments. Spring application resulted in relatively small emission peaks for the urea, LIMUS and AA+N-serve treatments with flux rates of approximately 25 g ha^{-1} d^{-1}. SuperU, ESN and eNtrench did not induce appreciable flux events.

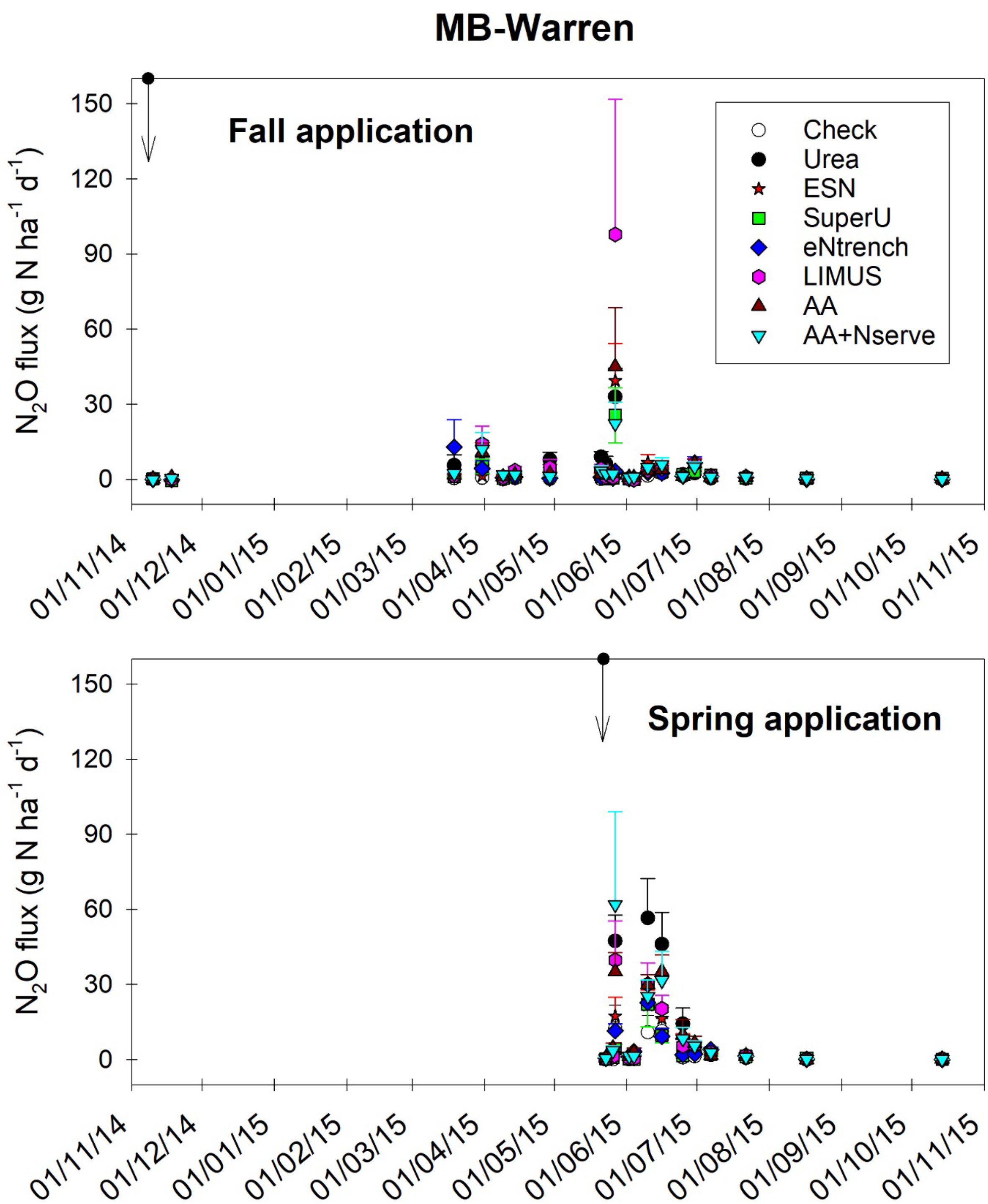
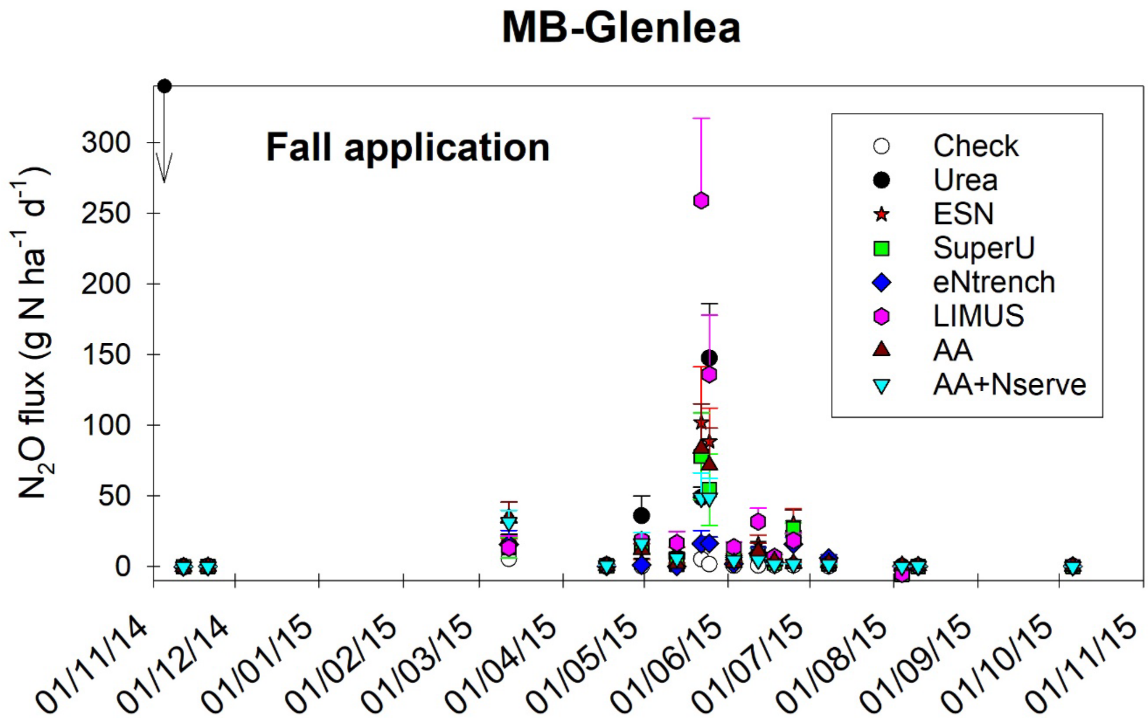


Fig. 3. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at MB-Warren. Arrows indicate the date of Fall or Spring fertilizer application.



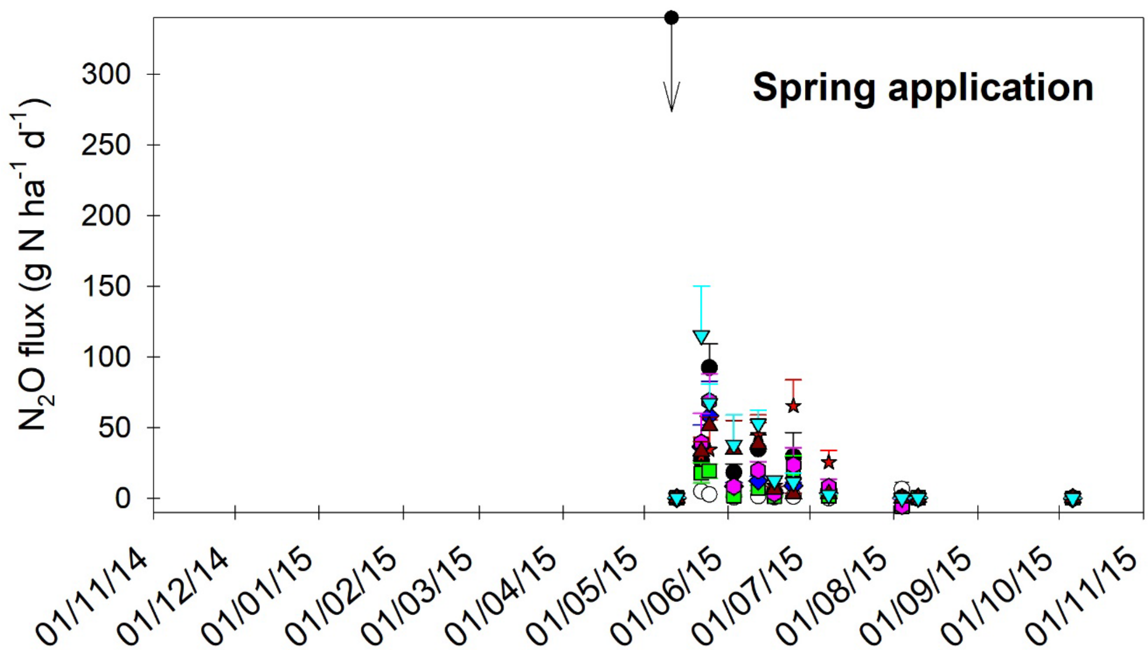


Fig. 4. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at MB-Glenlea. Arrows indicate the date of fall or spring fertilizer application.

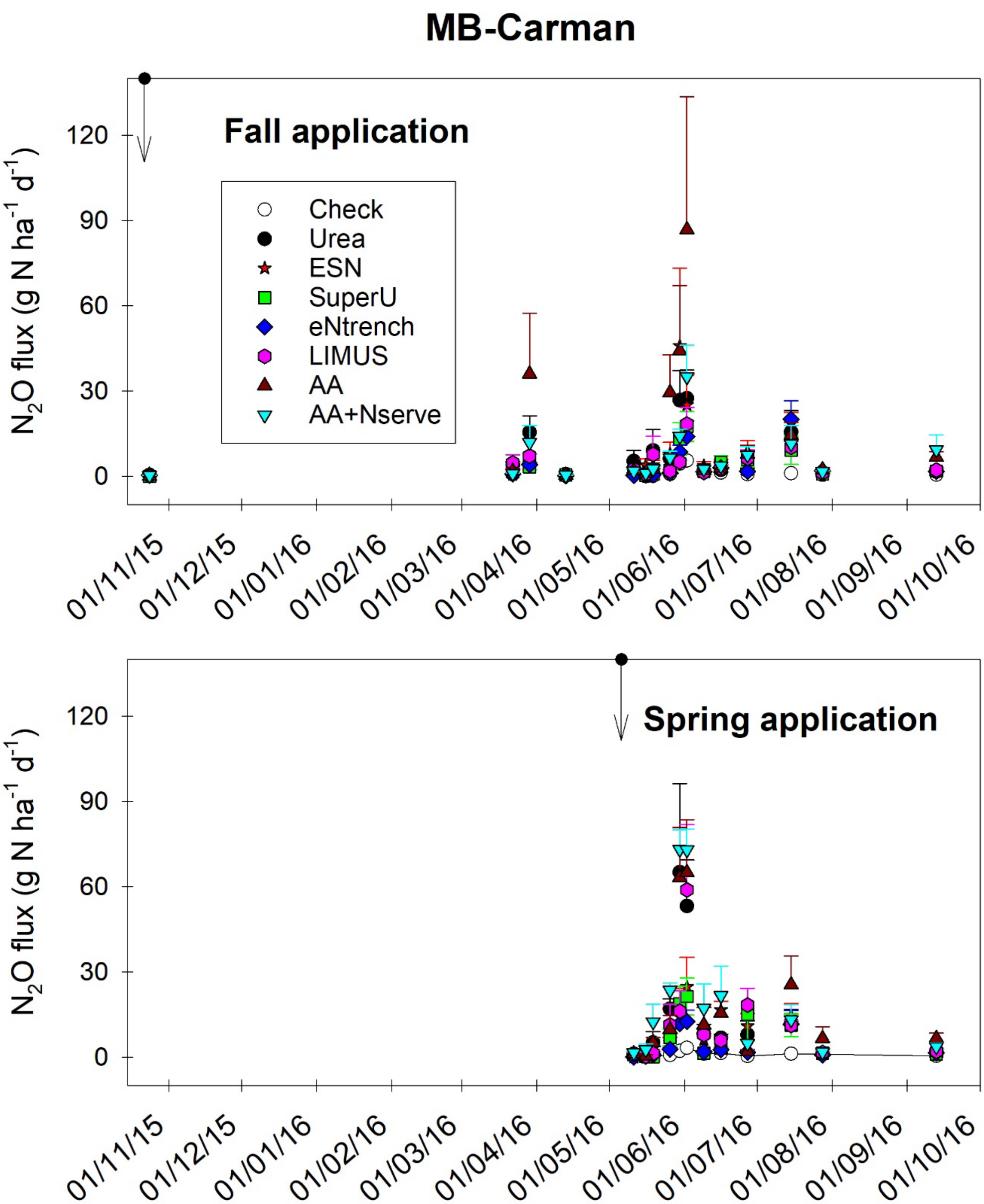


Fig. 5. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at MB-Carman. Arrows indicate the date of fall or spring fertilizer application.

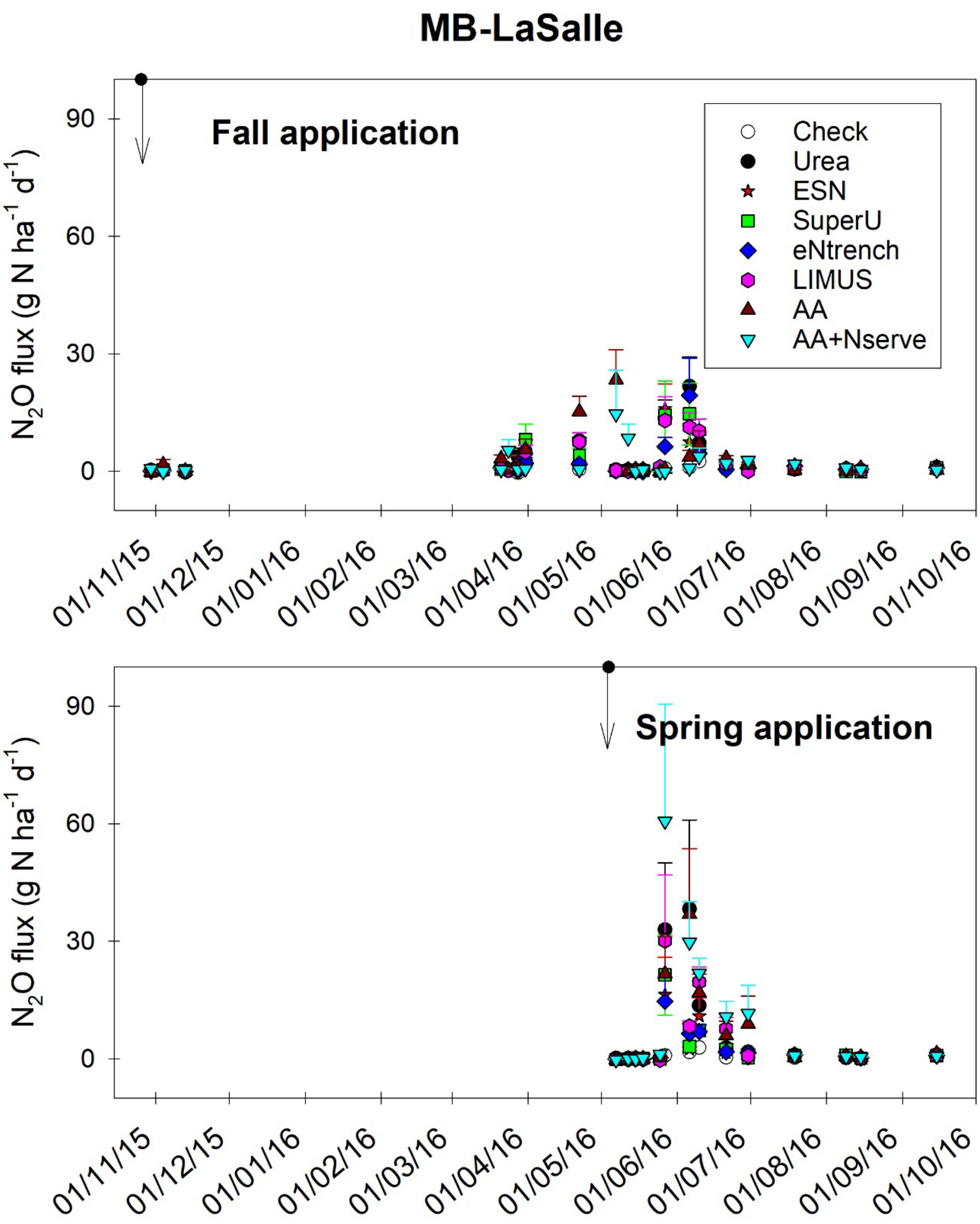


Fig. 6. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at MB-LaSalle. Arrows indicate the date of fall or spring fertilizer application.

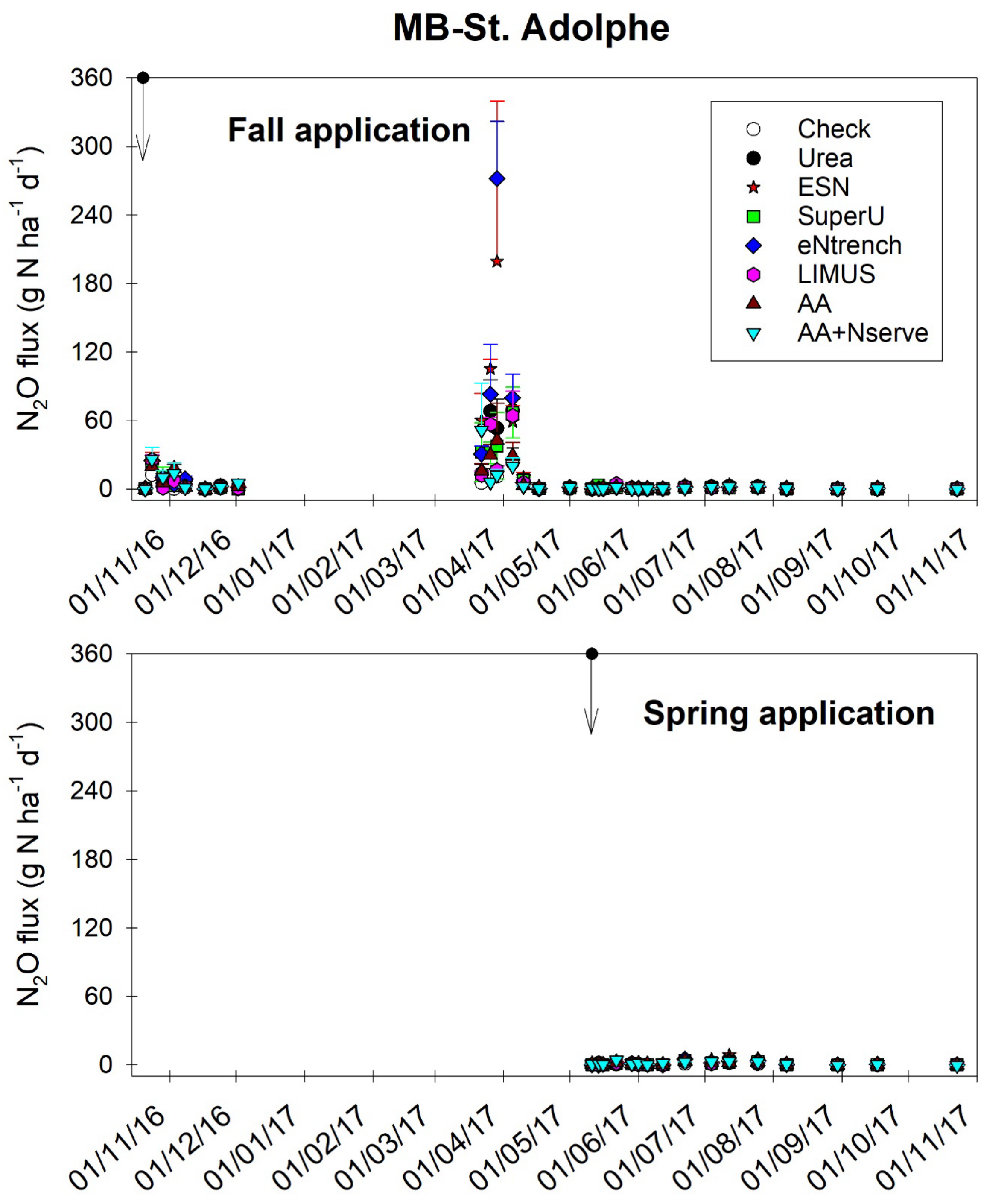
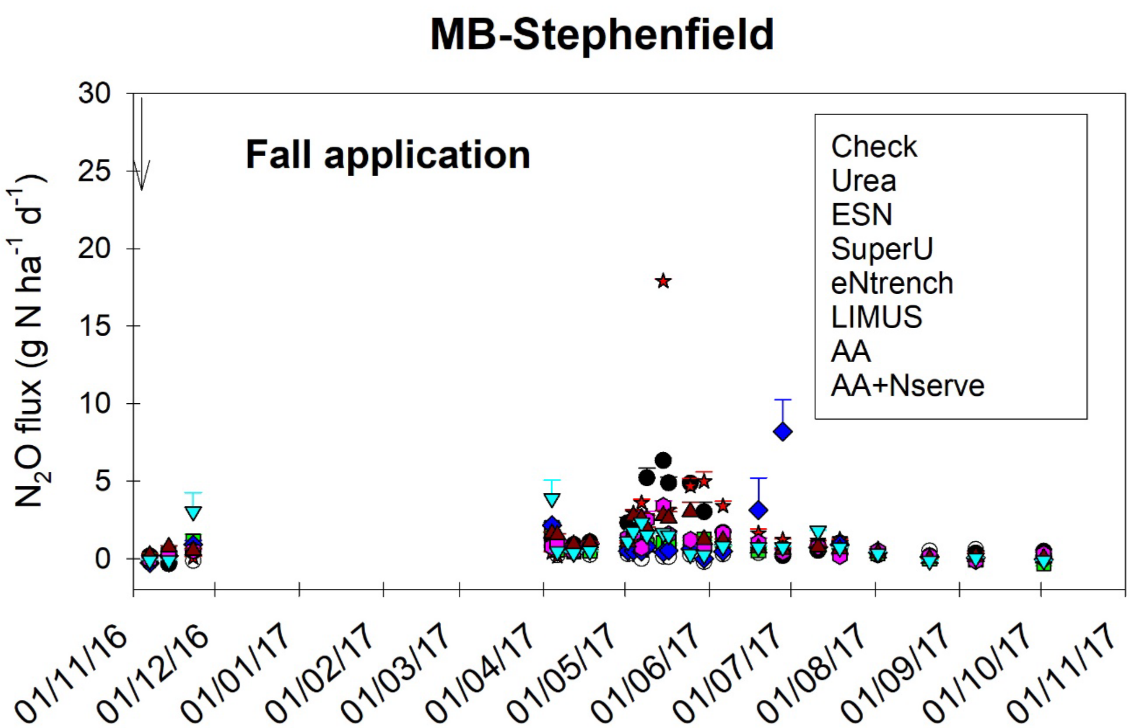


Fig. 7. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at MB-St. Adolphe. Arrows indicate the date of fall or spring fertilizer application.



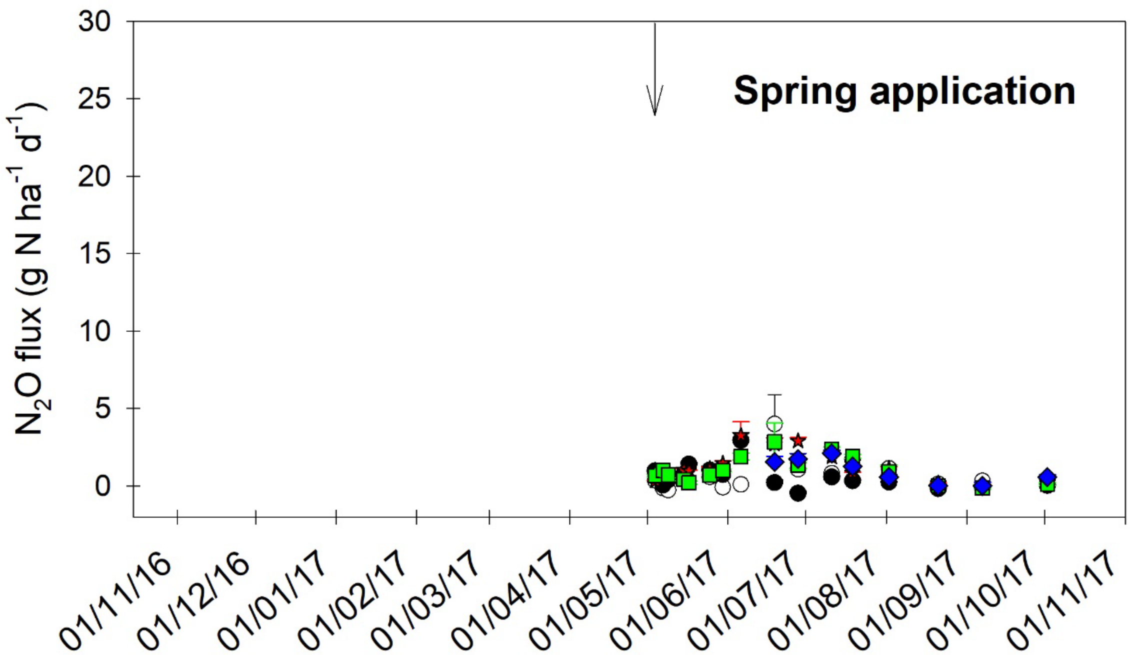


Fig. 8. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at MB-Stephenfield. Arrows indicate the date of fall or spring fertilizer application.

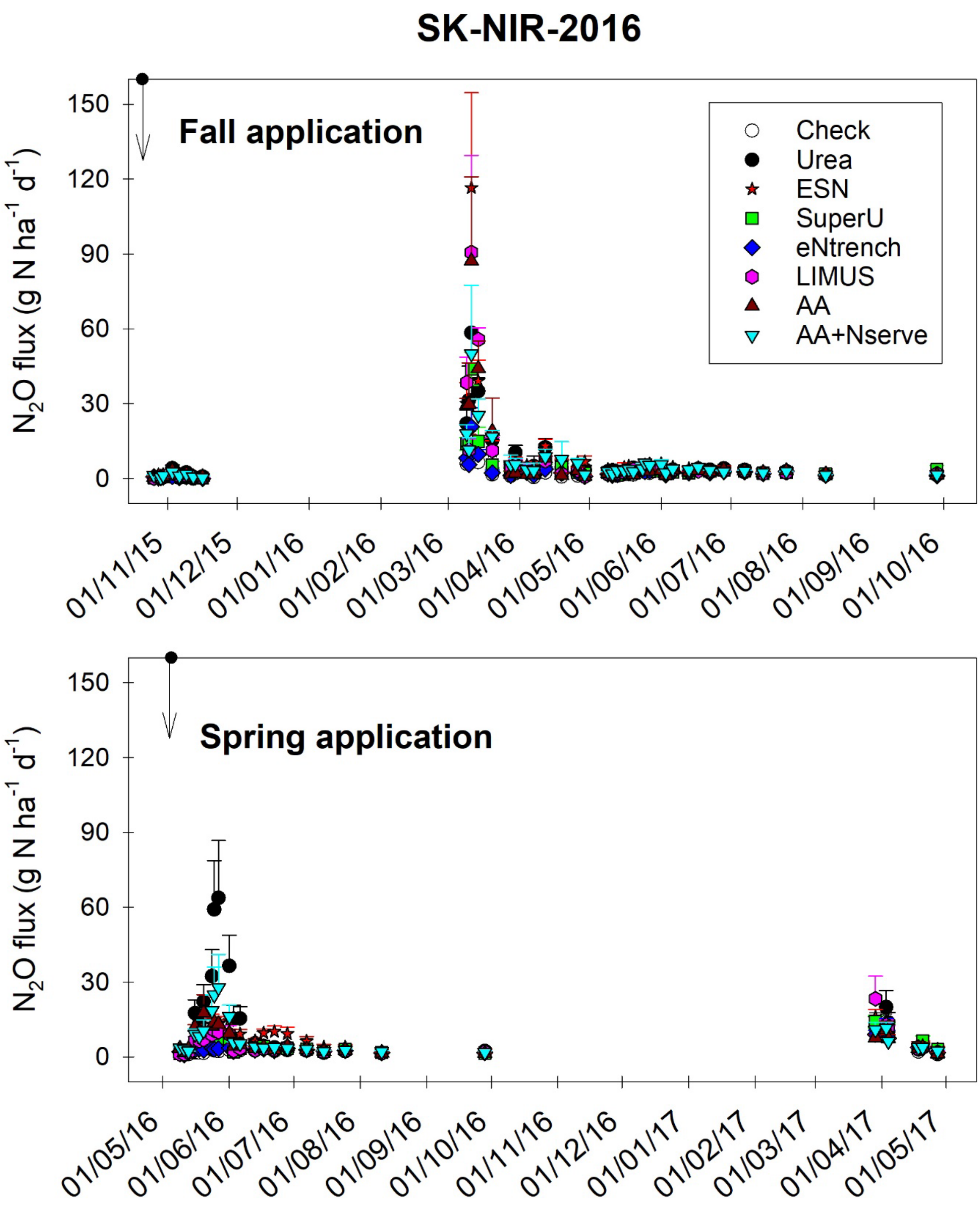


Fig. 9. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at SK-NIR (non-irrigated) site in 2016 crop year. Arrows indicate the date of fall or spring fertilizer application. NOTE: Fall AA plots were over fertilized due to a calculation error by PAMI.

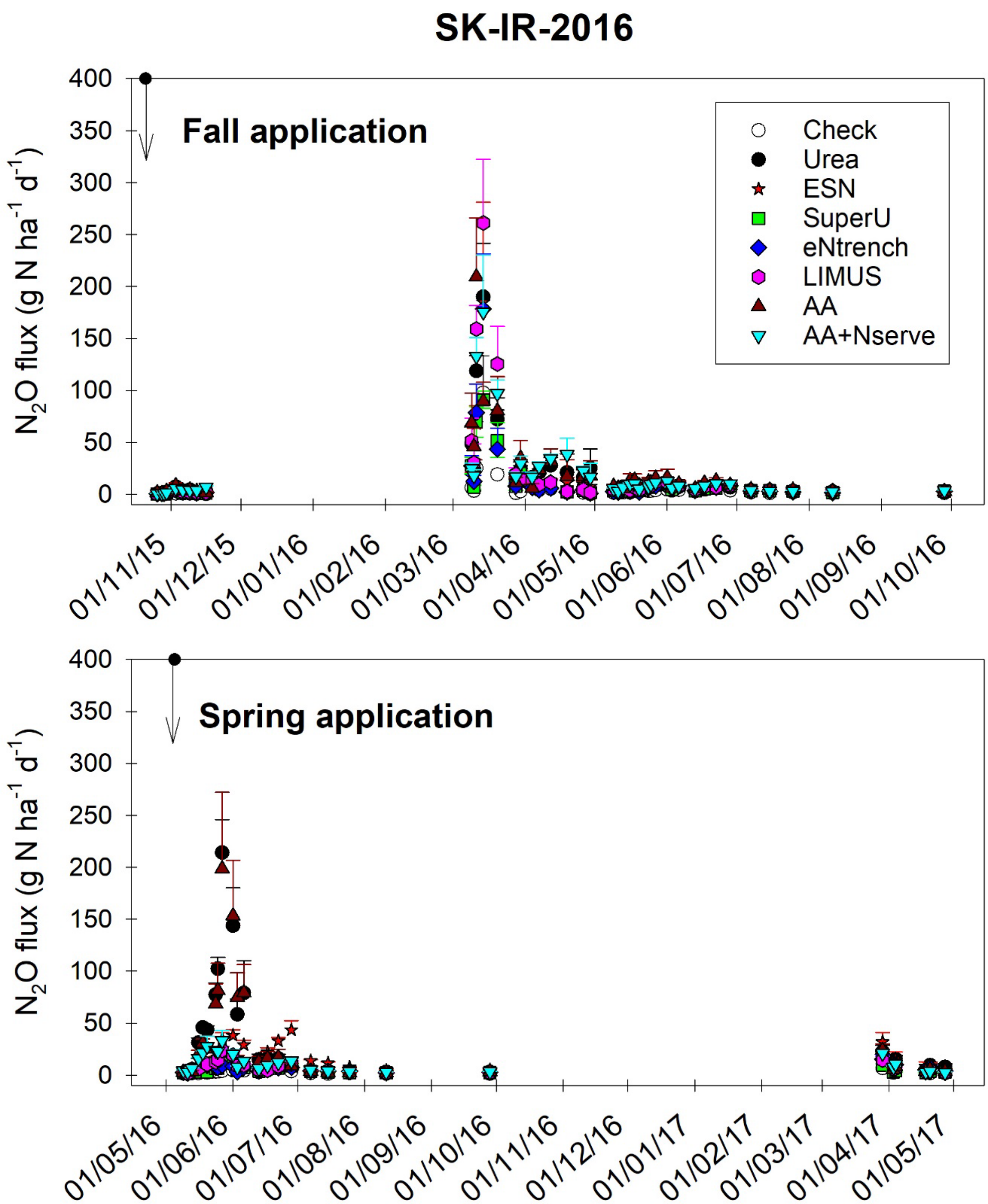


Fig. 10. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at SK-IR (irrigated) site in 2016 crop year. Arrows indicate the date of fall or spring fertilizer application. NOTE: Fall AA plots were over fertilized due to a calculation error by PAMI.

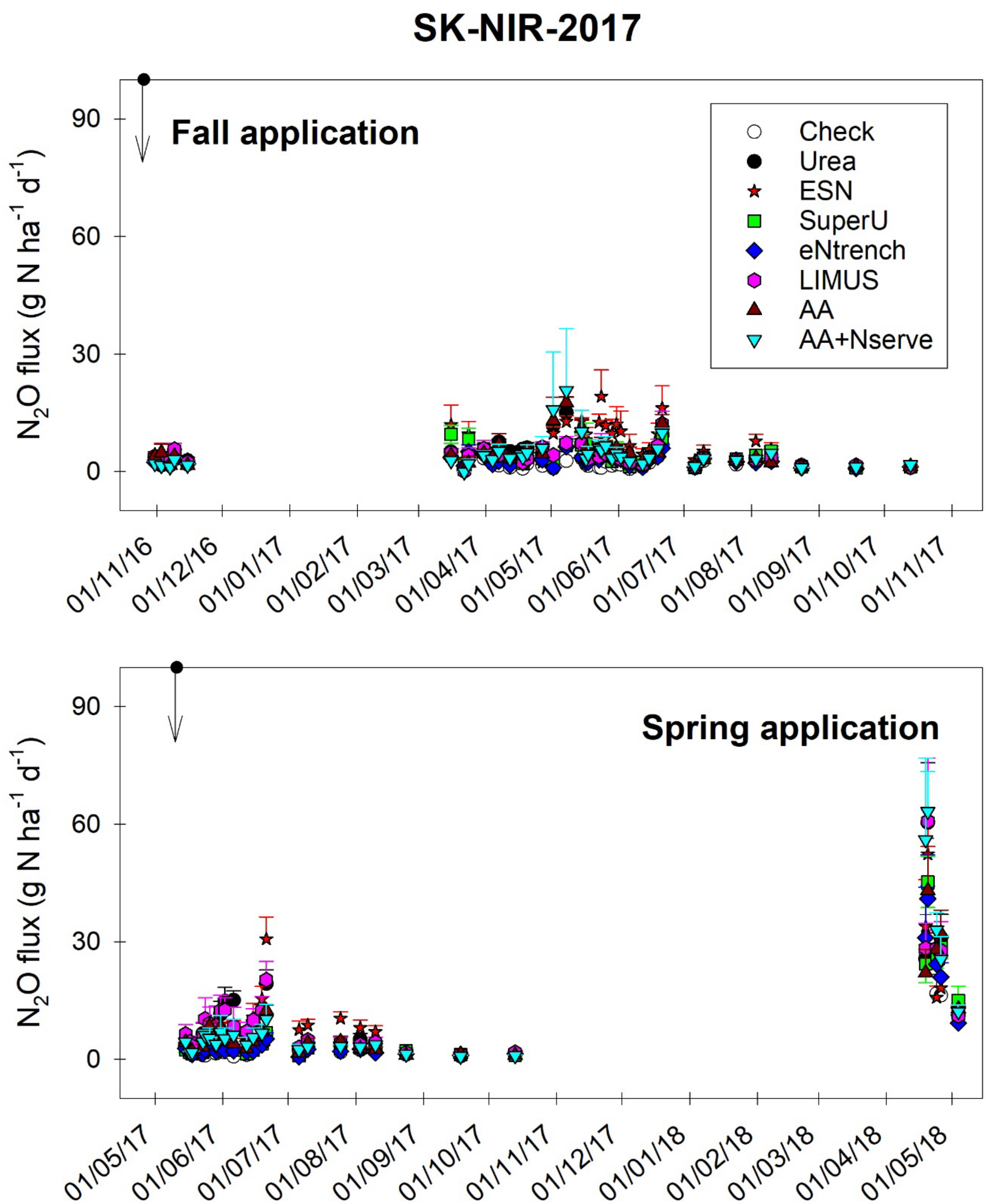


Fig. 11. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at SK-NIR (non-irrigated) site in 2017 crop year. Arrows indicate the date of fall or spring fertilizer application.

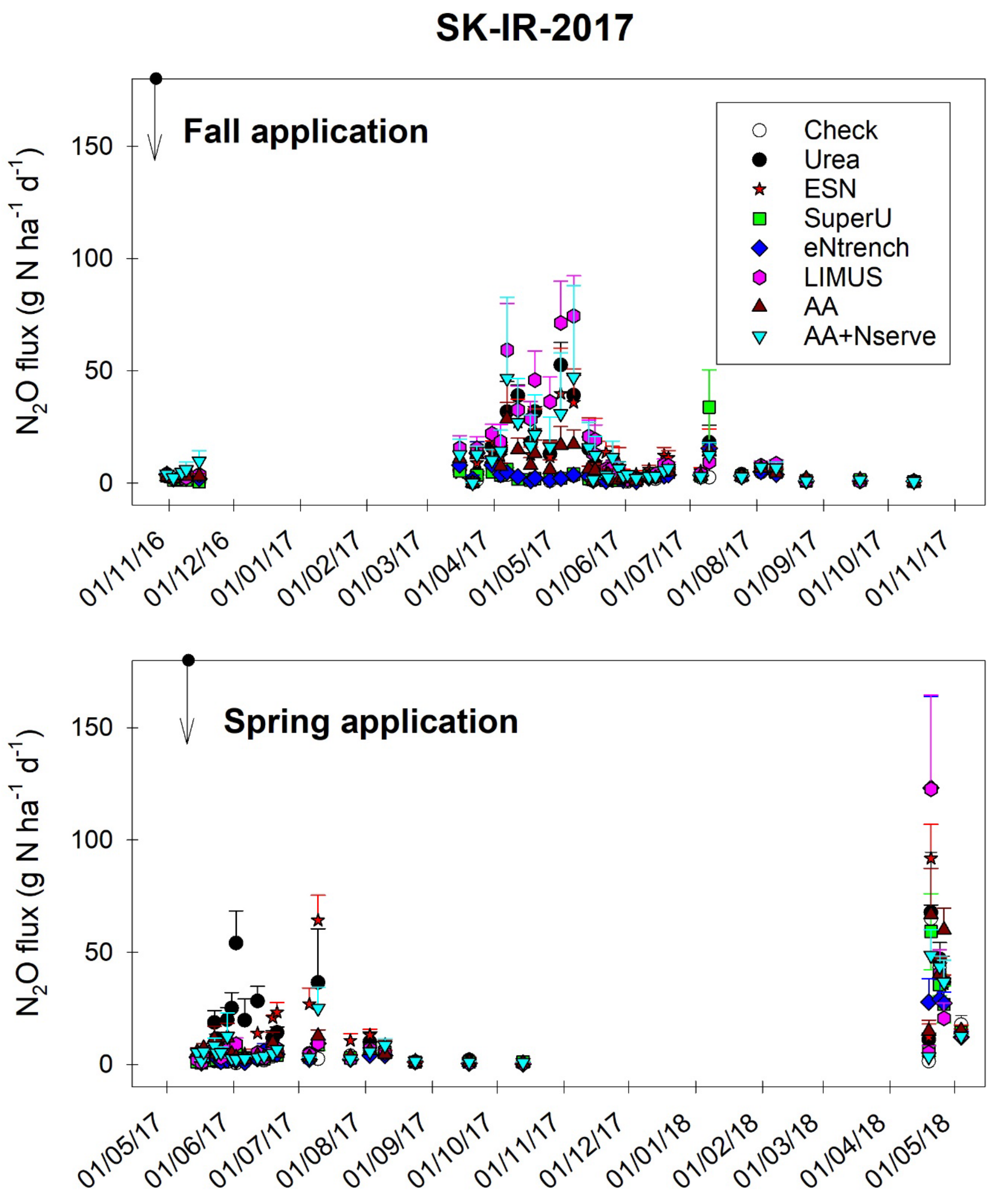


Fig. 12. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at SK-IR (irrigated) site in 2017 crop year. Arrows indicate the date of fall or spring fertilizer application.

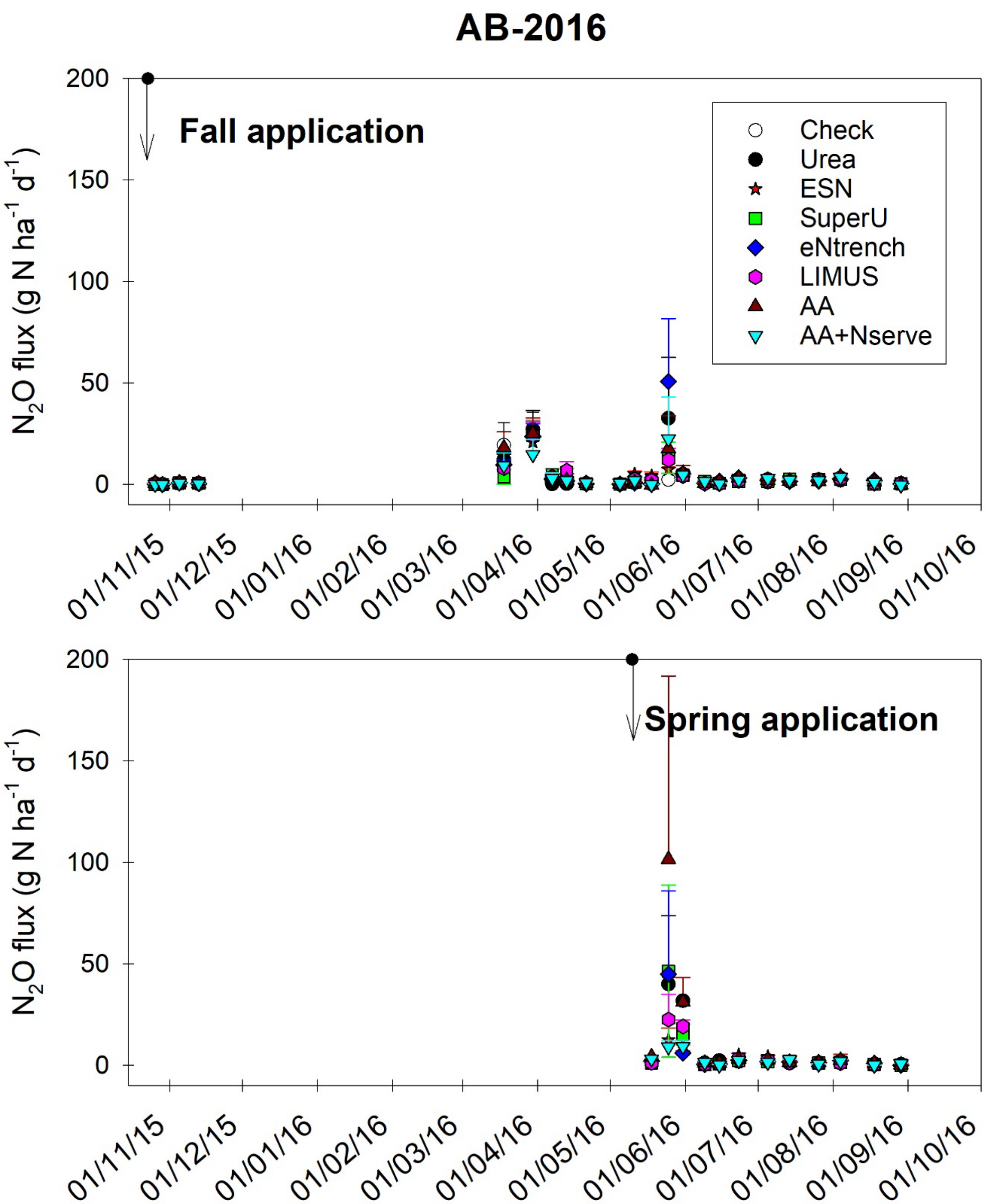


Fig. 13. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at AB-2016 site in 2016 crop year. Arrows indicate the date of fall or spring fertilizer application.

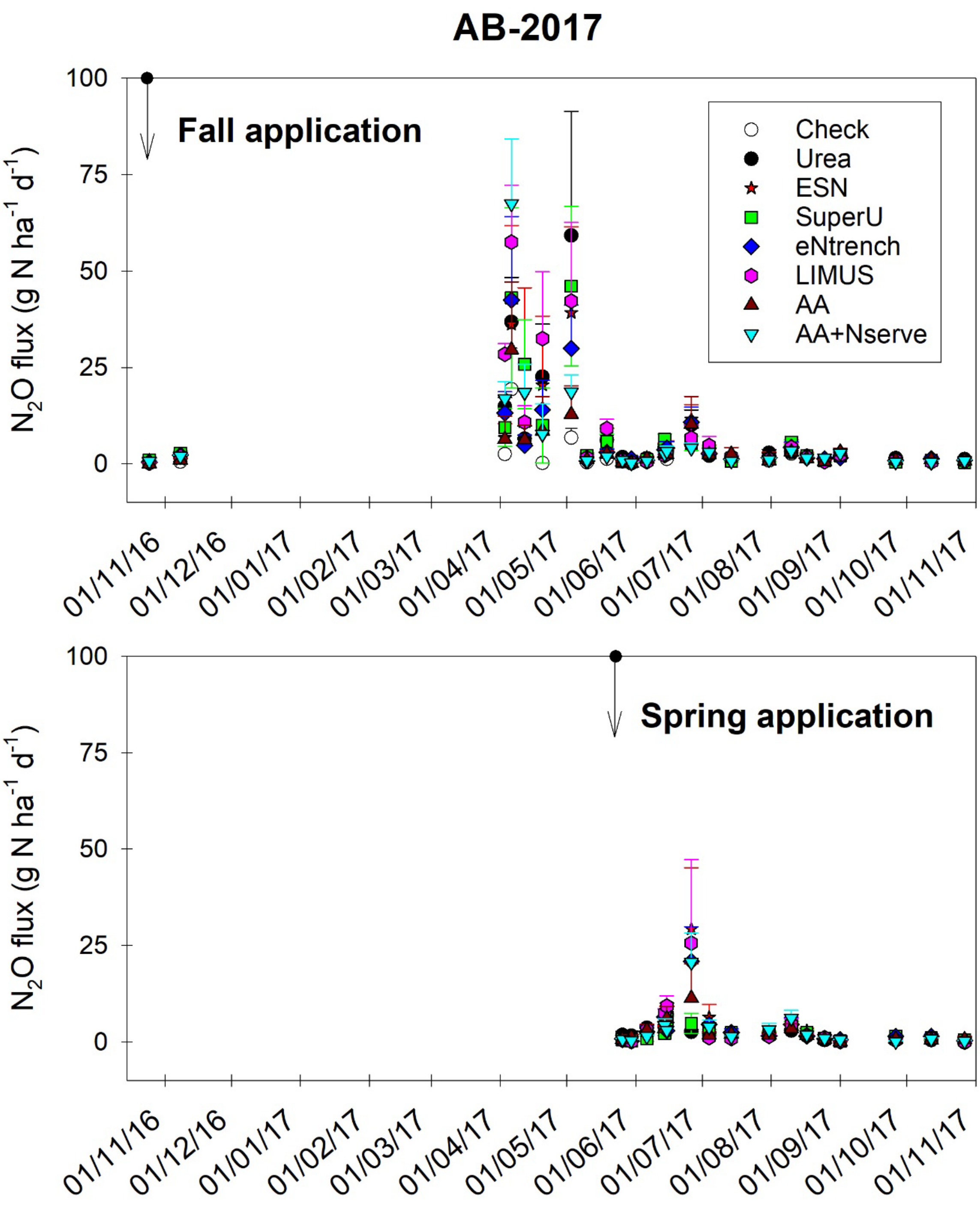


Fig. 14. Daily N_2O flux (g N ha^{-1} d^{-1}) as affected by timing and source of fertilizers at AB-2017 site in 2016 crop year. Arrows indicate the date of fall or spring fertilizer application.

2.1.2 Cumulative N_2O emissions

Effects of fertilizer source and application time on cumulative N_2O emissions varied between site-years (Table 2&3). At five of the twelve site-years (two from MB, two from SK and one from AB), fall application had significantly greater N_2O emissions compared to spring application, likely due to increased emissions during soil thawing in early spring. In contrast, spring application resulted in higher N_2O emissions than fall applications at two site-years (MB-Warren-2015, SK-NIR-2017). These results suggest a high dependence of fertilizer timing effect on environmental factors such as soil and weather conditions. The sites with more precipitation, especially those with more snows over the winter, are more likely to have greater N_2O emissions from fall than spring-applied fertilizers due to conditions conducive to thaw emissions from denitrification.

Fertilizer source effect also differed between site-years (Table 2&3). ANOVA analysis excluding unfertilized control plots showed significant source effects at nine site-years; three site-years (MB-St. Adolphe-2017, AB-2016, AB-2017) did not exhibit fertilizer source effects. Three enhanced efficiency nitrogen fertilizers had reduced N_2O emissions compared to conventional granular urea: ESN at one site-year (MB-Warren-2015); SuperU at four site-years (MB-Warren-2015, SK-NIR-2016, SK-IR-2016, and SK-IR-2017); and eNtrench at eight site-years (MB-Warren-2015, MB-Carman-2016, MB-La Salle-2016, MB-Stephenfield-2017, SK-NIR-2016, SK-IR-2016, SK-NIR-2017, and SK-IR-2017). Only LIMUS did not exhibit reduced N_2O emissions compared to granular urea alone. At all site-years, N_2O emissions from anhydrous ammonia applied with N-serve did not differ from anhydrous ammonium applied alone. Cumulative N_2O emissions were generally not affected by interactions of fertilizer source and application time, with the exceptions of MB-Glenlea-2015, MB-Stephenfield-2017 and SK-IR-2016, where N_2O emissions differed between fertilizer sources applied in fall but not for those applied in spring. Also, irrigated SK sites in 2016 and 2017 had greater emissions than non-irrigated sites.

These results highlight the importance of site-specific conditions on N_2O emissions. Among all N sources, eNtrench was most effective at reducing N_2O emissions at all site-years. SuperU was also effective at four of twelve site-years. Other sources including ESN and LIMUS had limited benefits in reducing N_2O emissions compared to conventional urea. Further studies are required to investigate under what conditions enhanced efficiency fertilizers can reduce N_2O emissions for crop production in Canadian Prairies.

2.1.3 Yield

Hail damage in 2017 at the irrigated and non-irrigated SK sites prevented calculation of grain yields. Instead, biomass yields were determined using a forage harvester. Similar to N_2O emissions, fertilizer treatment effect on yield of spring wheat varied between site-years (Table 4 &5). At all site-years except AB-2016, grain or biomass yield of spring wheat increased as a result of fertilizer N addition. At four site-years (MB-Warren, MB-Glenlea, MB-La Salle, SK-NIR-2016), spring application had higher spring wheat grain yield compared to fall application. Fertilizer source generally did not affect grain yield, except at MB-Warren and MB-St. Adolphe where ESN showed yield benefits compared to AA or urea. Compared to conventional urea, all enhanced efficiency N fertilizer sources did not negatively affect yield, most likely because N addition rates were at the recommended level based on soil tests and provincial guidelines. Recommendations are considered to be above the N response range.

2.1.4 Applied-N scaled emission factor and yield-scaled emission intensity

Applied-N scaled emission factor (EF) ranged between -0.37% and 4.71% across all twelve site-years (Table 6&7). All negative values were observed for fertilizer treatments at AB sites in 2016 and 2017, due to a high N_2O emission from the unfertilized control plot. MB-Glenlea-2015 and MB-Carman-2016 had the highest average EF across fertilizer treatments, at 2.08% and 1.65%, respectively. Fertilizer treatment effects on EF varied with site-years. Fall application significantly increased ($P<0.05$) EF at five site-years (MB-Glenlea-2015, MB-St. Adolphe-2017, SK-NIR-2016, SK-IR-2016, SK-IR-2017). Fertilizer source showed a significant effect on EF at all site-years except at AB-2016 and AB-2017. There was also significant source by time interaction effect at six site-years (MB-Warren-2015, MB-Glenlea-2015, MB-La Salle-2016, MB-St. Adolphe-2017, MB-Stephen-2017, and SK-IR-2016), suggesting the fertilizer source effect differed with application time. For example, EFs at MB-Warren-2015 were higher for urea alone than when EENFs were included for spring application treatment but were similar for fall application treatment. Spring application of SuperU and eNtrench showed some benefits to reducing EFs. For example, EFs associated with SuperU and eNtrench were lower than urea alone at three sites (MB-Warren-2015, SK-NIR-2016, SK-IR-2016) when fertilizers were applied in spring.

Use of N-serve with AA did not reduce EFs compared to AA alone at all site-years, irrespective of application time. It is interesting to note that irrigated SK sites had higher EFs than non-irrigated sites for the fall application treatments, but similar for spring application treatments.

2.1.5 Yield-scaled emission intensity

Yield-scaled emission intensity was generally not affected by Time by Source interaction at all site-years except MB-Glenlea-2015 and SK-IR-2016 (Table 8&9). Fall application resulted in higher emission intensity than spring application at five site-years (MB-Glealea-2015, MB-St. Adophe-2017, SK-NIR-2016, SK-IR-2016, AB-2017). Fertilizer N addition generally increased emission intensity over unfertilized control plots on most site-years. There were significant fertilizer source effects at nine site-years. SuperU significantly reduced ($P<0.05$) emission intensity at four site-years (MB-Warren-2015, SK-NIR-2016, SK-IR-2016, SK-IR-2017) compared to urea alone. The eNtrench treatment also reduced emission intensity at five site-years (MB-Warren-2015, MB-Glenlea-2015, MB-Stephen-2017, SK-NIR-2016, SK-IR-2016). In contrast, ESN and LIMUS did not effectively reduce emission intensity compared to urea alone. Including N-serve did not affect the emission intensity of AA treatments at all site-years. Across fertilizer treatments, emission intensity varied with site-years, with values ranging between 0.08 and 0.64 kg N_2O-N Mg^{-1}.

2.1.6 Source effect across site-years

Among the nine site-years with significant source effect, the overall reduction of N_2O emissions by eNtrench and SuperU was 53 and 49%, respectively, compared with conventional urea (Fig. 15). The N_2O reduction index (ratio to urea) of eNtrench and SuperU was also significantly reduced, at 53% and 63% of urea, respectively. Similarly, applied N-scaled emission factor and yield-scaled emission intensity was also significantly lower in the treatments of eNtrench and

SuperU, compared with other treatments. These results confirm the consistent effect of using inhibitor-based stabilized products to reduce N_2O emissions from cropland, especially when the early growing season is moist.

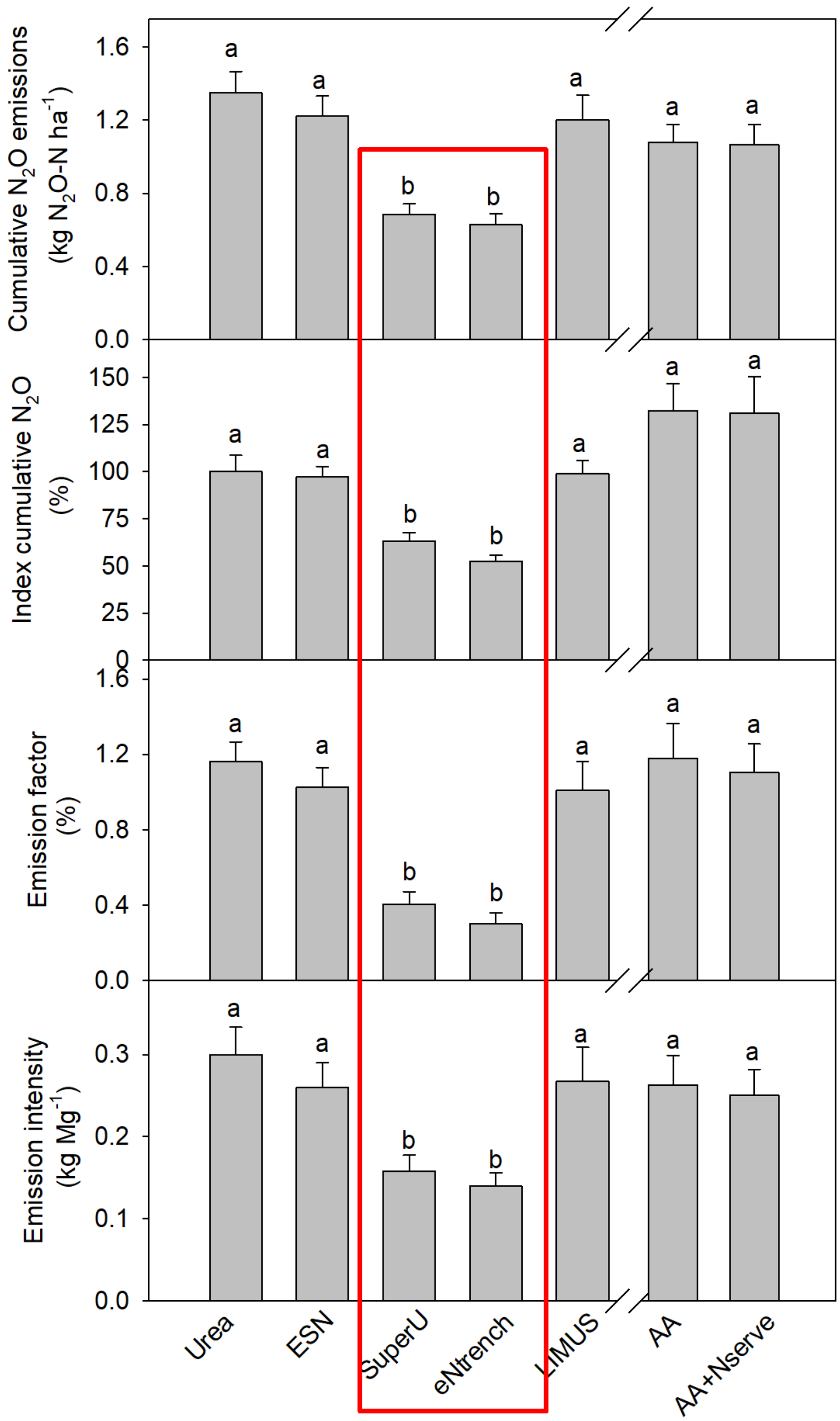


Fig. 15. Mean cumulative emissions, N_2O reduction index (ratio to urea), emission factor and emission intensity across nine site-years with significant source effects as influenced by N sources. Different lowercase letters indicate significant at P=0.05.

2.2 Project outcomes

This project has completed significant activities relating to technology transfer. Main messages from the research results were efficiently provided to the public through communications with growers, crop consultants, industry staff, policymakers and other scientists. Public field tours of Manitoban field sites were carried out in the summers of 2015, 2016 and 2017, and in Alberta and Saskatchewan in 2016 and 2018. Also, many stakeholders visited field sites during the project. Two photos showing outreach activities are provided in Fig. 16.

Some of the project outcomes in the form of technology transfer activities, i.e. field tours, invited presentations, meetings are listed as scientific achievements in this report.

Fig. 16. Project outreach activities in Manitoba for this activity; touring with a stakeholder (KOCH Agronomics) (left) and Dr. Kevin Baron of Tenuta's Laboratory describing plot layout and treatments to attendees of a public tour at a field site in Manitoba (right).

2.3 Important lessons learned

This project successfully and thoroughly investigated the time and source of fertilizer N management within the 4R Nutrient Stewardship program in terms of their effectiveness to achieve high production and nutrient use efficiency while minimizing environmental impacts. It was designed to resolve gaps in our understanding of the interaction between timing of fertilizer N addition (fall, spring) and enhanced efficiency fertilizers to increase N use efficiency and reduce N_2O emissions to the atmosphere. Preliminarily statistical analyses of N_2O emissions in area-, applied N- and yield-scaled have been completed for all twelve site-years across the prairie provinces. The following are summaries of some of the important lessons learned from this project:

1) Fall application is inferior to spring application concerning N losses as N_2O emissions, as it resulted in higher area-scaled N_2O emissions at five site-years, higher applied N-scaled emissions at six site-years, and the higher yield-scaled emission intensity at five site-years. Also, fall application reduced grain yield of spring wheat at four site-years. This project concludes that fall application should not be recommended in the prairies provinces for

agronomic and environmental reasons. The existing 4R best management practices for the region, which generally regard fall fertilizer application as inferior to spring application, is reasonable.

2) Enhanced efficiency fertilizers can be used to reduce N_2O emissions from cropland while maintaining or improving crop productivity. A lack of fertilizer source effect on grain yield at most site-years was not unexpected given that fertilizer N was applied at recommended rates. Compared to conventional urea, the stabilized products with nitrification, or nitrification and ureases inhibitors were effective at reducing N_2O emissions. For example, eNtrench reduced area-scaled N_2O emissions at eight site-years, applied N-scaled emission factors at three site-years, and the yield-scaled emission intensity at five site-years. In contrast, ESN and LIMUS were not as effective as eNtrench or SuperU, showing only occasional benefits.

3) Including N-serve did not show any benefit over anhydrous ammonia alone on agronomy or reduction of N_2O emissions, suggesting a limited benefit to using inhibitors with AA to reduce N_2O emissions.

4) The overall message is therefore positive: 4R practices can reduce the negative impact of food production on the environment and farmers may benefit from voluntarily implementing 4R practices to reduce N_2O emissions through a carbon offset marker. Results of the study will be used to calculate the offset dollar value of carbon credits from the use of enhanced efficiency fertilizers across prairie provinces.

Table 2. ANOVA results (P value) on cumulative N_2O emissions at 12 site-years.

	DF	2015		2016		2017		2016		2017		2016	2017
		MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-St. Ad	MB6-Stephen	SK1-NIR GrantP	SK2-IR GrantP	SK3-NIR GrantRP	SK4-IR GrantRP	AB1-SA16	AB2-SA16
Time	1	0.044	0.008	0.163	0.519	<0.001	0.667	0.009	<0.001	0.002	0.318	0.165	<0.001
Source (no check)	6	0.002	0.003	<0.001	0.009	0.249	<0.001	<0.001	<0.001	<0.001	<0.001	0.434	0.612
Time×Source	6	0.308	0.018	0.457	0.229	0.552	0.035	0.064	0.017	0.557	0.086	0.740	0.695

Notes:

For SK sites in 2016, AA and AA+N-serve were not included for the SAS analysis due to an incomplete dataset.

At MB and AB sites, for the spring application treatment, cumulative emissions were calculated by inclusion of the over-winter flux from the check.

The SK sites had measured a year-period for both fall and spring application treatment.

Table 3. Cumulative N_2O emissions (kg N ha^{-1}) at 12 site-years, as affected by fertilizer treatments.

Treatments	2015		2016		2017		2016		2017		2016	2017
	MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-Adolphe	MB6-Stephen	SK1-NIR	SK2-IR	SK3-NIR	SK4-IR	AB1-SA16	AB2-SA16
Time												
Fall	0.46 b	1.81 a	0.87	0.47	1.34 a	0.22	0.85 a	2.43 a	0.80 b	1.58	0.70	1.37 a
Spring	0.60 a	1.32 b	0.98	0.52	0.54 b	0.26	0.69 b	1.42 b	1.01 a	1.40	0.53	0.44 b
Source												
Check	0.20	0.22	0.18	0.11	0.45	0.07	0.43	1.09	0.50	0.71	0.62	0.51
Urea	0.84 a	2.07 ab	1.06 ab	0.62 ab	0.93	0.28 ab	1.14 a	3.18 a	1.00 ab	1.94 a	0.70	0.96
ESN	0.47 b	2.13 ab	0.95 abc	0.38 bc	1.53	0.21 abc	1.06 a	2.42 ab	1.26 a	2.11 a	0.49	1.04
SuperU	0.36 b	1.08 b	0.67 bc	0.39 bc	0.84	0.17 bc	0.66 bc	1.22 c	0.75 bc	0.87 b	0.57	0.88
eNtrench	0.34 b	0.97 b	0.56 c	0.33 c	1.61	0.10 c	0.48 c	1.44 bc	0.57 c	0.86 b	0.68	0.88
LIMUS	0.74 ab	2.47 a	0.90 abc	0.53 abc	0.79	0.23 ab	0.85 ab	2.21 abc	0.97 ab	1.89 ab	0.53	1.14
AA	0.65 ab	1.68 ab	1.75 a	0.81 a	0.72	0.51 a	-	-	0.89 abc	1.24 ab	0.90	0.59
AA+N-serve	0.64 ab	1.89 ab	1.33 a	0.80 a	0.66	0.36 a	-	-	0.90 abc	1.53 ab	0.44	0.85
Avg.	0.58	1.76	1.03	0.55	1.01	0.27	0.84	2.09	0.91	1.49	0.62	0.90

Notes:

Means were compared by LSD. Different letters within Time or Source indicate significant at p=0.05.

For SK sites in 2016, AA and AA+N-serve were not included due to an incomplete dataset.

At MB and AB sites, for the spring application treatment, cumulative emissions were calculated by inclusion of the over-winter flux from the check.

The SK sites had measured a year-period for both fall and spring application treatment.

Table 4. ANOVA results (P value) on wheat yield at 12 site-years.

	DF	2015		2016		2017		2016		2017		2016	2017
		MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-St. Ad	MB6-Stephen	SK1-NIR GrantP	SK2-IR GrantP	SK3-NIR GrantRP	SK4-IR GrantRP	AB1-SA16	AB2-SA16
Time	1	<0.001	<0.001	0.436	<0.001	0.578	0.039	0.002	0.971	0.225	0.057	0.634	0.134
Source (no check)	6	0.005	0.274	0.552	0.771	0.012	0.153	0.042	0.134	0.567	0.517	0.140	0.524
Time×Source	6	0.879	0.749	0.783	0.067	0.012	0.963	0.445	0.103	0.607	0.183	0.739	0.288

Notes: For SK sites in 2016, AA and AA+N-serve were not included for the SAS analysis due to an incomplete dataset. Data for 2017 crop year at SK sites are above-ground biomass due to 100% hail damage on grain.

Table 5. Grain yield of wheat (Mg ha^{-1}) at 12 site-years, as affected by fertilizer treatments.

Treatments	2015		2016		2017		2016		2017		2016	2017
	MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-Adolphe	MB6-Stephen	SK1-NIR	SK2-IR	SK3-NIR	SK4-IR	AB1-SA16	AB2-SA16
Time												
Fall	2.92 b	2.46 b	3.46	3.79 b	5.25	3.69 a	4.10 b	4.51	9.52	18.63	4.48	3.24
Spring	3.13 a	2.75 a	3.53	4.09 a	5.21	3.24 b	4.24 a	4.51	10.10	19.49	4.53	3.47
Source												
Check	2.06	1.41	2.65	2.79	4.22	1.72	3.57	3.81	6.64	14.92	4.43	2.96
Urea	3.23 ab	2.75	3.66	4.18	5.21 b	3.44	4.36 ab	4.74	9.52	20.02	4.19	3.48
ESN	3.31 a	2.77	3.71	4.12	5.75 a	3.51	4.28 ab	4.73	9.39	18.41	4.77	3.26
SuperU	3.28 a	2.63	3.69	4.04	5.47 ab	3.43	4.28 ab	4.54	9.97	19.43	4.37	3.79
eNtrench	3.26 ab	2.85	3.58	3.99	5.38 ab	3.47	4.16 b	4.57	9.09	18.59	4.73	3.43
LIMUS	3.25 ab	3.03	3.59	4.12	5.30 ab	4.20	4.40 a	4.64	9.67	19.08	4.43	3.49
AA	2.88 b	2.62	3.63	4.19	5.25 b	4.30	-	-	10.27	19.11	4.49	3.22
AA+N-serve	2.96 ab	2.81	3.48	4.07	5.27 b	3.64	-	-	10.75	18.80	4.65	3.24
Avg.	3.03	2.61	3.50	3.94	5.23	3.46	4.17	4.51	9.81	19.06	4.51	3.36

Notes: For SK sites in 2016, AA and AA+N-serve were not included due to an incomplete dataset. Data for 2017 crop year at SK sites are above-ground biomass due to 100% hail damage on grain.

Means were compared by LSD. Different letters within Time or Source indicate significant at *p*=0.05.

Table 6. ANOVA results (P value) on applied-N scaled emission factors at 12 site-years.

	DF	2015		2016		2017		2016		2017		2016	2017
		MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-St. Ad	MB6-Stephen	SK1-NIR GrantP	SK2-IR GrantP	SK3-NIR GrantRP	SK4-IR GrantRP	AB1-SA16	AB2-SA16
Time	1	0.971	<0.001	0.133	0.235	<0.001	0.217	0.009	<0.001	0.082	0.047	0.098	<0.001
Source (no check)	6	<0.001	<0.001	<0.001	<0.001	0.005	0.003	<0.001	<0.001	<0.001	0.001	0.322	0.610
Time×Source	6	0.004	<0.001	0.425	0.005	0.015	0.009	0.064	0.017	0.557	0.086	0.708	0.696

Notes: For SK sites in 2016, AA and AA+N-serve were not included for the SAS analysis due to an incomplete dataset.

Table 7. Applied-N scaled emission factors (%) at 12 site-years, as affected by fertilizer treatments.

Treatments	2015		2016		2017		2016		2017		2016	2017
	MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-Adolphe	MB6-Stephen	SK1-NIR	SK2-IR	SK3-NIR	SK4-IR	AB1-SA16	AB2-SA16
Fall												
Urea	0.49 ab	3.15 b	1.51 ab	0.62 a	1.71 abc	0.50 a	0.86 ab	1.64 a	0.39 ab	1.26 ab	0.15	1.12
ESN	0.31 b	2.69 b	1.50 ab	0.49 a	3.83 ab	0.34 a	1.13 a	1.41 a	0.82 a	1.23 ab	-0.02	0.99
SuperU	0.23 b	1.98 bc	0.77 b	0.52 a	1.39 bc	0.24 a	0.44 ab	0.62 a	0.29 ab	0.13 b	-0.01	0.93
eNtrench	0.16 b	1.02 c	0.87 b	0.35 a	4.37 a	0.09 a	0.12 b	0.84 a	0.00 b	0.01 b	0.26	0.74
LIMUS	0.71 a	4.71 a	0.95 b	0.58 a	1.26 bc	0.41 a	0.90 a	2.02 a	0.30 ab	2.01 a	0.03	1.27
AA	0.41 ab	2.51 bc	3.15 a	1.05 a	0.88 c	0.30 a	-	-	0.45 ab	0.53 ab	0.12	0.31
AA+N-serve	0.36 ab	1.97 bc	1.69 ab	0.57 a	0.59 c	0.45 a	-	-	0.39 ab	1.18 ab	0.00	0.72
Avg.	0.38	2.58	1.49	0.60 a	2.00	0.33	0.69	1.31	0.38	0.91	0.08	0.87
Spring												
Urea	0.79 a	1.87 abc	1.90 ab	0.87 ab	0.19 a	0.36 b	1.07 a	1.76 a	0.75 ab	1.10 a	0.01	-0.22
ESN	0.24 bc	2.49 ab	1.47 ab	0.29 b	0.47 a	0.23 b	0.59 ab	0.75 ab	1.00 a	1.48 a	-0.26	0.08
SuperU	0.10 c	0.36 c	1.14 ab	0.30 b	0.16 a	0.17 b	0.18 b	-0.42 b	0.22 ab	0.01 a	-0.10	-0.17
eNtrench	0.13 c	1.01 bc	0.59 b	0.30 b	0.25 a	0.05 b	0.00 b	-0.28 b	0.04 b	0.12 a	-0.15	0.00
LIMUS	0.38 bc	1.40 abc	1.83 ab	0.63 b	0.09 a	0.23 b	0.25 b	-0.20 b	0.79 ab	0.25 a	-0.22	0.00
AA	0.51 ab	1.45 abc	2.90 a	0.99 ab	0.19 a	1.48 a	-	-	0.42 ab	0.38 a	0.44	-0.14
AA+N-serve	0.53 ab	2.57 a	2.77 a	1.44 a	0.24 a	0.71 ab	-	-	0.50 ab	0.32 a	-0.37	-0.04
Avg.	0.38	1.59	1.80	0.69	0.23	0.46	0.42	0.32	0.53	0.52	-0.09	-0.07

Notes: For SK sites in 2016, AA and AA+N-serve were not included due to an incomplete dataset.
Means were compared by LSD. Different letters within Time or Source indicate significant at p=0.05.

Table 8. ANOVA results (P value) on yield scaled emission intensity at 12 site-years.

	DF	2015		2016		2017		2016		2017		2016	2017
		MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-St. Ad	MB6-Stephen	SK1-NIR GrantP	SK2-IR GrantP	SK3-NIR GrantRP	SK4-IR GrantRP	AB1-SA16	AB2-SA16
Time	1	0.181	<0.001	0.236	0.370	<0.001	0.576	0.004	<0.001	0.033	0.226	0.086	<0.001
Source (no check)	6	<0.001	0.002	<0.001	0.007	0.187	0.001	<0.001	<0.001	0.003	0.001	0.469	0.470
Time×Source	6	0.492	0.012	0.521	0.214	0.403	0.141	0.075	0.01	0.385	0.029	0.720	0.813

Notes: For SK sites in 2016 crop year, AA and AA+N-serve were not included for the SAS analysis due to an incomplete dataset. Data for 2017 crop year at SK sites are based on above-ground biomass due to 100% hail damage on grain.

Table 9. Yield scaled emission intensity (kg N_2O-N Mg^{-1}) at 12 site-years, as affected by fertilizer treatments.

Treatments	2015		2016		2017		2016		2017		2016	2017
	MB1-Warren	MB2-Glenlea	MB3-Carman	MB4-La Salle	MB5-Adolphe	MB6-Stephen	SK1-NIR	SK2-IR	SK3-NIR	SK4-IR	AB1-SA16	AB2-SA16
Time												
Fall	0.17	0.79 a	0.27	0.14	0.27 a	0.07	0.22 a	0.58 a	0.09 b	0.09	0.16	0.41 a
Spring	0.20	0.49 b	0.30	0.13	0.11 b	0.09	0.17 b	0.32 b	0.11 a	0.07	0.11	0.14 b
Source												
Check	0.10	0.15	0.07	0.04	0.11	0.05	0.12	0.28	0.09	0.05	0.14	0.17
Urea	0.26 a	0.77 a	0.29 ab	0.15 ab	0.18	0.09 a	0.26 a	0.67 a	0.11 ab	0.10 ab	0.16	0.28
ESN	0.14 abc	0.77 a	0.26 ab	0.09 b	0.26	0.06 ab	0.25 a	0.51 ab	0.14 a	0.11 a	0.11	0.32
SuperU	0.11 bc	0.43 ab	0.18 b	0.10 b	0.15	0.05 ab	0.15 bc	0.27 b	0.08 b	0.05 c	0.13	0.23
eNtrench	0.10 c	0.33 b	0.16 b	0.08 b	0.31	0.03 b	0.12 c	0.32 b	0.07 b	0.05 bc	0.14	0.27
LIMUS	0.23 ab	0.86 a	0.25 ab	0.13 ab	0.15	0.05 ab	0.20 ab	0.49 ab	0.10 ab	0.10 ab	0.12	0.34
AA	0.23 ab	0.65 ab	0.48 a	0.20 a	0.14	0.13 a	-	-	0.09 ab	0.07 abc	0.19	0.19
AA+N-serve	0.22 ab	0.68 ab	0.38 a	0.20 a	0.12	0.12 a	-	-	0.09 ab	0.08 abc	0.10	0.27
Avg.	0.18	0.64	0.29	0.14	0.19	0.08	0.20	0.45	0.10	0.08	0.14	0.27

Notes: For SK sites in 2016, AA and AA+N-serve were not included due to an incomplete dataset. Data for 2017 crop year at SK sites are based on above-ground biomass due to 100% hail damage on grain.

Means were compared by LSD. Different letters within Time or Source indicate significant at p=0.05.

3. Greenhouse Gas and Non-GHG Impacts

3.1 Qualitative discussion about the GHG benefits resulting from the completed project, including immediate benefits and potential future impacts

Results of this project show the benefits of enhanced efficiency fertilizers in reductions in N_2O emissions without negatively affecting crop productivity. We clearly showed that fall application is inferior to spring application concerning the overall agronomy and reduction of N_2O emissions. SuperU and eNtrench showed more consistent benefits in reduction of N_2O emissions on area-, applied N- and yield-scales. These results are particularly important to develop the 4R-based best management practices and thus provide guidelines for enhancing nutrient use efficiency and reducing GHG emissions for crop production on prairie provinces. Based on the project outcome, several factsheets were posted to the National Centre for Livestock and the Environment website in terms of 4R recommendations (http://umanitoba.ca/faculties/afs/ncle/publications/info_sheets.html). Numerous presentations were given to increase knowledge transfer through communications between growers, crop consultants, industry staff, policy makers and scientist.

The results have garnered a lot of media interest, and Dr. Tenuta has spoken on the project, benefits of enhanced efficiency fertilizers, and 4R Nutrient Stewardship in prairie provinces and across the country. Dr. Tenuta is in the process of calculating the offset dollar value of C credits from the use of enhanced efficiency fertilizers in Alberta. He has done so for Saskatchewan, Manitoba, and Ontario at the requests of those governments. Those analyses show the possible offsets of about $100,000 per year. The results of this project will provide the evidence to support estimates for offsets for Alberta and the rest of the Prairies.

3.2 Quantification of expected annual GHG benefits projected over ten years (and further if applicable), including both direct impacts from implementation of the project and future impacts based on market adoption.

The results of this project will be important to support and help the governments to achieve the short-term (10-15 years) and long-term (50-100 years) GHG reduction goals. Using Manitoba agriculture as an example, Dr. Tenuta has conducted a model-based case study to predict N_2O offsets based on 4R practice implementation. Results showed that 4R practices will play important roles in achieving reduction targets in Manitoba. Specifically, the right use of enhanced efficiency fertilizers is potentially effective to reduce N_2O emissions by one third compared to the present level without decreasing N rates which could negatively affect productivity. The results of this project will help to develop incentives to reduce GHG emissions over ten-years or even longer periods.

3.3 Discussion about the immediate and potential future non-GHG benefits resulting from the completed project.

We noticed a reduction of spring wheat grain yield for fall fertilizer application, compared with spring application. Use of enhanced efficiency fertilizers generally did not affect grain yield, which is expected as N rates were set according to provincial recommendations. These results will help to improve the 4R best management practices and to achieve higher nutrient use efficiency further. Additional studies are required to investigate whether the use of enhanced efficiency fertilizers can increase or maintain crop productivity at reduced N rates.

4. Scientific Achievements

Peer-reviewed journal publications are now being summarized from each site-year. An overall paper summarizing results across all site-years is also expected. There are three grad students, Shakila Thilakarathna (U of A), Cheyne Ogilvie (U of S), and Matthew Wood (U of M), working on this project while completing their requirements for M.Sc. degrees.

Some of the project outcomes in the form of technology transfer activities are listed here:

Videos created on 4R nutrient management and posted to Soil Ecology, University of Manitoba, You Tube Channel (https://www.youtube.com/channel/UCfL0EKIg0Nu6_3DTU-4ENKQ)

Factsheets posted to the National Centre for Livestock and the Environment website on a) Selecting The Right Placement Of Fertilizer N In Manitoba, and b) Selecting The Right Source Of Fertilizer N In Manitoba. (http://umanitoba.ca/faculties/afs/ncle/publications/info_sheets.html)

Twitter Series entitled “Hot Air, Cold Truths”. Series by Dr. Tenuta helping growers understand issue of greenhouse gas emissions from cropped soils and how they are concerned. (@soilecologyUMan)

Breaking Down the Hot Air and Cold Truth About Carbon Emissions. Real Agriculture. Posted October 31, 2016 by Kelvin Hoepner. (https://www.realagriculture.com/2016/10/breaking-down-the-hot-air-and-cold-truth-about-carbon-emissions/)

In the battle to mitigate global warming farmers’ nitrogen use will be scrutinized. Manitoba Co-operator. Posted October 14, 2016 by Alan Dawson (https://www.manitobacooperator.ca/news-opinion/news/global-warming-fight-could-see-farmers-nitrogen-use-under-fire/).

Credits and Costs: Understanding the Carbon Balance of Annual Cropping. Real Agriculture. Posted January 23, 2017 by Kelvin Heppner (https://www.realagriculture.com/tag/mario-tenuta/).

Changing Nitrogen Use to Avoid Taxes. Grain News. March 8, 2017 by Leeanne Minogue. (https://www.grainews.ca/2017/03/08/changing-nitrogen-use-to-avoid-taxes/)

April 8, 2016. Project Annual Meeting. Co-ordinated by Dr. Tenuta. Held Winnipeg, Manitoba

April 22, 2016. Invited oral presentation “Nitrous Oxide Emissions and Global Climate Warming” to the Chinese Academy of Sciences. Meeting held in Urumqi, China.

May 12, 2016. Meeting and field tour with Mr. Ray Dowbenko, Agrium, Calgary, Alberta, to discuss project activities and results. Meeting held in Winnipeg, Manitoba

May 14-17, 2016. Oral presentation “Evaluating the use of enhanced efficiency nitrogen fertilizer products to reduce nitrous oxide emissions under irrigated and non-irrigated conditions in Saskatchewan” to the Canadian Society of Soil Science Annual Meeting. Meeting held in Kamloops, British Columbia.

June 29, 2016. Meeting and field tour with Mr. Garth Whyte, CEO of Fertilizer Canada to discuss and show project activities and 4R nutrient management research and outreach. Meeting held in Winnipeg and Carman, Manitoba.

July 13, 2016. University of Manitoba Grower 4R Field Day. Held at the project site near La Salle, Manitoba.

July 28, 2106. Meeting and field tour with Mr. Tom Jensen of IPNI to discuss 4R research and outreach activities. Meeting held in Winnipeg, Manitoba.

August 9, 2016. Field day and workshop organized by the University of Manitoba for Agrium and Cargill staff. Included presentation by Dr. Tenuta on 4R nutrient management and project results and tour of the project site at Carman, Manitoba. Indoor workshop held at the Carman Research Station, Carman, Manitoba.

Sept 19, 2016. Meeting with Mrs. Pat Flaten, Research Director of Western Grains Research Foundation to discuss project activities and results. Meeting held in Saskatoon, Saskatchewan.

October 12, 2016. Meeting and field tour with Dr. Rigas Karamanos of Koch Agronomic Services Canada to discuss project results and activities. Meeting held in Winnipeg, Manitoba.

October 19, 2016. Meeting with Mr. Sean Goertzen, Environmental Policy Director with Keystone Agricultural Producers to discuss 4R management and greenhouse gas reductions. Meeting held in Winnipeg, Manitoba.

October 26, 2016. Invited oral presentation to the Canola Discovery Forum "The Future of Nitrogen Fertilizers". Meeting held in Winnipeg, Manitoba.

Nov 7-10, 2016. Oral presentation "A Matter of Timing and Source: Enhanced Efficiency Nitrogen Fertilizers and Products to Reduce Nitrous Oxide Emissions in the Prairie Provinces" to the Canadian 4R Research Network Annual Meeting at the Joint meeting of the American Society of Agronomy, Soil Science Society of America and Crop Science Society of America in Phoenix, Arizona.

Nov 7-10, 2016. Oral presentation "Evaluating the use of enhanced efficiency nitrogen fertilizer products to reduce nitrous oxide emissions under irrigated and non-irrigated conditions in Saskatchewan" to the Joint meeting of the American Society of Agronomy, Soil Science Society of America and Crop Science Society of America in Phoenix, Arizona.

Nov 7-10, 2016. Oral presentation "Can Use of 4R Nutrient Stewardship Practices Meet Required Emissions Reductions from Cropped Soils in the Short-Term?" to Joint meeting of the American Society of Agronomy, Soil Science Society of America and Crop Science Society of America in Phoenix, Arizona.

Nov 17, 2016. Invited oral presentation to the Canadian Soil Conservation Council meeting "Digging into Soil Health". Meeting held in Moncton, New Brunswick.

Nov 23, 2016. Invited host of 4R Table Discussion at Ag Excellence Conference. Held in Calgary, Alberta.

Dec 1, 2016. Invited oral presentation "Can Use of 4R Nutrient Stewardship Practices Meet Required Emissions Reductions from Cropped Soils in Manitoba?" and panel speaker at the 4R Nutrient Stewardship Panel. Meeting held in Ottawa, Ontario.

Jan 4, 2017. Invited oral presentation "Farming in the Future – How will N_20 Emissions Affect Fertilizing and Cropping Practices?" at St. Jean Farm Days. St. Jean, Manitoba.

Jan 11, 2017. Invited oral presentation "4R Nitrogen Management to Limit N_2O Emissions from Cropland" at the Fertilizer Canada Farm Management Canada 4R Webinar Series.

Jan 19, 2017. Invited oral presentation "Nitrogen Loss When Applied At Shallow Depths" at Manitoba Ag Days. Meeting held in Brandon, Manitoba.

Feb 1, 2017. Invited oral presentation "Carbon Sequestration, N_2O, Taxes and Reduction Targets from a

Grower's Point of View" to the Indian Head Agricultural Research Foundation annual meeting. Meeting held in Weyburn, Saskatchewan.

Feb 2-3, 2017. Oral presentation "What Will it Take to Reduce N_2O Emissions from Manitoba Field Crops to Meet Short-term Emission Reduction Targets?" to the Manitoba Society of Soil Science Annual Meeting. Meeting held in Winnipeg, Manitoba.

Feb 2-3, 2017. Oral presentation "Fall and Spring Applied Enhanced Efficiency Nitrogen Fertilizers on Spring Wheat Yield in Manitoba" to the Manitoba Society of Soil Science Annual Meeting. Meeting held in Winnipeg, Manitoba.

Feb 22, 2017. Invited presentation "Managing N Fertilizers to Reduce Nitrous Oxides Emissions: Just Hot Air?" to the Fertilizer Canada and Kelburn Farms 4R Nutrient Management Grower Workshop. Held at Ste. Adolphe, Manitoba.

March 3, 2017. Invited presentation "Research Innovation and Opportunity" to the Saskatchewan Government Offsets workshop organized by Fertilizer Canada. Meeting held in Regina, Saskatchewan.

March 9, 2017. Meeting with Dr. Rigas Karamanos to discuss project activities and results. Meeting held in Winnipeg, Manitoba.

March 9, 2017. Invited oral presentation "Research Innovation and Opportunity" to the Manitoba Government Greenhouse Gas Offsets Workshop. Meeting held in Winnipeg, Manitoba.

March 14, 2017. Invited oral presentation "Managing N Fertilizers to Reduce Nitrous Oxides Emissions:

Just Hot Air?" to the Agvise Agronomy Workshop. Meeting held in Portage la Prairie, Manitoba.

March 15, 2017. Invited oral presentation "Various Ramblings on Nitrogen Management from the Soil Ecology Laboratory" to the Manitoba Soil Fertility Advisory Committee. Meeting held in Winnipeg, Manitoba.

March 23, 2017. Invited oral presentation "Soil Health from Molecule to Ecosystem: The Curious Case of Nitrogen" to the Departments of Horticulture and Plant, Soil and Microbial Sciences, Michigan State University. Meeting at East Lansing, Michigan.

March 28, 2017. Invited presentation "Carbon: Discussion on a Taxing Issue" to the Canterra Seeds Agronomy Workshop. Meeting held in Carberry, Manitoba.

5. Next Steps

1) Analysis of samples for N contents in plant tissue is ongoing for further assessment on fertilizer N use efficiency by crops.
2) More data analysis will be conducted to compile results across all site-years and journal papers will be published from each site. An overall summary report/paper will also be published.
3) Further studies are required to investigate whether the use of enhanced efficiency fertilizers can increase or maintain crop productivity at reduced N rates for major crops in prairie provinces (e.g., canola).
4) Estimate emission factors for fall and spring N additions and stacking of enhanced efficiency fertilizer products for Alberta, Saskatchewan, and Manitoba based on the results of this project and other relevant projects to provide a better understanding of a national inventory of N_2O emission.
5) Continue analysis of data and use a model approach to estimate offsets of carbon credits from the use of a 4R strategy for the Prairies.
6) Use data from the current project to validate process models to better predict GHG emissions from croplands on Prairies.