# Nitrogen Source Effects on Soil Nitrous Oxide Emissions from Strip-Till Corn

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Nitrogen (N) application to crops generally results in increased nitrous oxide ($N_2O$) emissions. Commercially available, enhanced-efficiency N fertilizers were evaluated for their potential to reduce $N_2O$ emissions from a clay loam soil compared with conventionally used granular urea and urea-ammonium nitrate (UAN) fertilizers in an irrigated strip-till (ST) corn (*Zea mays* L.) production system. Enhanced-efficiency N fertilizers evaluated were a controlled-release, polymer-coated urea (ESN), stabilized urea, and UAN products containing nitrification and urease inhibitors (SuperU and UAN+AgrotainPlus), and UAN containing a slow-release N source (Nfusion). Each N source was surface-band applied (202 kg N ha$^{-1}$) at corn emergence and watered into the soil the next day. A subsurface-band ESN treatment was included. Nitrous oxide fluxes were measured during two growing seasons using static, vented chambers and a gas chromatograph analyzer. All N sources had significantly lower growing season $N_2O$ emissions than granular urea, with UAN+AgrotainPlus and UAN+Nfusion having lower emissions than UAN. Similar trends were observed when expressing $N_2O$ emissions on a grain yield and N uptake basis. Loss of $N_2O$–N per kilogram of N applied was <0.8% for all N sources. Corn grain yields were not different among N sources but greater than treatments with no N applied. Selection of N fertilizer source can be a mitigation practice for reducing $N_2O$ emissions in strip-till, irrigated corn in semiarid areas.

NITROUS OXIDE is produced in soils mostly from nitrification and denitrification processes with agriculture contributing ~67% of the total U.S. $N_2O$ emissions (USEPA, 2010). Nitrous oxide has a global warming potential (GWP) approximately 298 times greater than that of $CO_2$ (Solomon et al., 2007), thus the importance of developing methods to reduce $N_2O$ emissions in agricultural systems. Nitrogen fertilization is essential for optimizing crop yields and economic returns in irrigated cropping systems in the U.S. Central Great Plains (Archer et al., 2008; Archer and Halvorson, 2010; Maddux and Halvorson, 2008). Nitrogen fertilizer application generally increases $N_2O$ production from cropping systems (Bouwman et al., 2002; Hao et al., 2001; Dusenbury et al., 2008; Mosier et al., 2006, Halvorson et al., 2008, 2010a; Van Groenigen et al., 2010).

Data available for analyzing $N_2O$ emission impacts on net GWP in irrigated crop production systems is limited (Hao et al., 2001; Mosier et al., 2006; Snyder et al., 2009; Archer and Halvorson, 2010). Snyder et al. (2009) presented an extensive review of greenhouse gas emissions (GHG) from cropping systems but found little information available on the effects of commercially available, controlled-release and stabilized-N sources on $N_2O$ emissions. They suggest that more research on enhanced-efficiency N fertilizers is needed to thoroughly evaluate their agronomic impact and effects on $N_2O$ losses. Olson-Rutz et al. (2009) define enhanced-efficiency fertilizers as "fertilizers that reduce loss to the environment and/or increase nutrient availability compared with conventional fertilizers." Akiyama et al. (2010) reported N fertilizer containing a nitrification inhibitor reduced $N_2O$ emissions 38% and polymer-coated fertilizer 35% compared with conventionally used N fertilizer. Fertilizers containing urease inhibitor were not effective in reducing $N_2O$ emissions. Halvorson et al. (2010a, b) reported reductions in $N_2O$ emissions from N fertilizers containing both urease and nitrification inhibitors, and with polymer-coated urea fertilizer compared with conventionally used granular urea. Jumadi et al. (2008) and Bronson et al. (1992) also reported reduced $N_2O$ emissions with the use of a nitrification inhibitor added to urea.

**Abbreviations**: ANOVA, analysis of variance; CC, continuous corn; CT, conventional-till; DOY, day of year; ESN, polymer-coated urea; ESNssb, ESN subsurface band; GHG, greenhouse gas; GWP, global warming potential; NT, no-till; ST, strip-till; SuperU, stabilized granular urea; UAN, urea-ammonium nitrate; UAN+AP, UAN with AgrotainPlus; UAN+Nf, UAN with Nfusion; WFPS, water-filled pore space.

Venterea et al. (2005, 2010) found N source influenced $N_2O$ emissions from corn production systems in Minnesota with greatest $N_2O$ emissions from anhydrous ammonia application, with significantly lower emissions from urea-ammonium nitrate (UAN) and urea. Hyatt et al. (2010) reported reduced $N_2O$ emissions with a single preplant application of a polymer-coated urea to a potato (*Solanum tuberosum* L.) crop on a loamy sand soil compared with multiple smaller applications (five to six) of urea and ammonium nitrate during the growing season. Venterea et al. (2011b) found lower $N_2O$ emissions from a stabilized urea N source (contained urease and nitrification inhibitors) applied to corn compared with polymer-coated urea but not less than conventional urea from a silt loam soil in southern Minnesota in both conventionally tilled and no-till production systems.

The N source comparison work of Halvorson et al. (2010a) on $N_2O$ emissions involved different tillage and cropping systems, but it did not allow the direct comparison of $N_2O$ emissions from urea, polymer-coated urea (ESN) (registered trademark product of Agrium Advanced Technologies, Loveland, CO), and SuperU (registered trademark product of Agrotain International, St. Louis, MO) under the same experimental conditions. Halvorson et al. (2010b) compared the effects of several enhanced-efficiency N fertilizers on soil $N_2O$ emissions under an irrigated, no-till–(NT), continuous corn (CC) production system, with significant reductions (up to 53%) in $N_2O$ emissions from some enhanced-efficiency N fertilizers when compared with urea. Halvorson et al. (2010a) reported differences in the effectiveness of ESN in reducing $N_2O$ emissions from CT–CC and NT–CC production systems, with no differences in $N_2O$ emissions between ESN and urea in CT–CC but significant reductions with ESN (34%) in the NT–CC compared with urea. Drury et al. (2006) reported that zone tillage or strip tillage and shallow (2-cm depth) N placement are potential management practices that may reduce $N_2O$ emissions from fine-textured soils in cool, humid climates that are cropped to corn. Thus, tillage system can have an effect on $N_2O$ emissions. Strip till has produced irrigated corn yields similar to moldboard plow tillage in the Central Great Plains near Fort Collins, CO, demonstrating its potential to replace moldboard plow tillage (unpublished data, A.D. Halvorson, USDA–ARS, 2008–2010).

The main objective of this study was to evaluate the effects of enhanced-efficiency fertilizer N sources (ESN, stabilized granular urea [SuperU], stabilized UAN [UAN + AgrotainPlus], and slow-release UAN [UAN + Nfusion]) on growing season $N_2O$ emissions compared with those from conventionally used granular urea and liquid UAN applications within an irrigated, strip-till (ST), CC production system. In addition, $CO_2$ and $CH_4$ emissions were monitored and reported here for future use but not discussed in detail. A second objective was to evaluate the possible agronomic benefits of the enhanced-efficiency N fertilizers on grain yield and N uptake, and relate $N_2O$ emissions from each N source on a grain yield and N uptake basis.

## Materials and Methods

The study was located in a ST, CC field at the Agricultural Research Development and Education Center (ARDEC)

in northeastern Colorado, near Fort Collins, CO (40°39′6″ N; 104°59′55″ W; 1535 m above sea level). The region has a semiarid temperate climate with typical mean annual temperature of 8.9°C and rainfall of 383 mm yr$^{-1}$ (average from 1893–2010), with an average of 69, 46, 41, 37, 32, and 29 mm of precipitation in May, June, July, August, September, and October, respectively, or growing season total of 254 mm (May–October). The soil is a Fort Collins clay loam, classified as fine-loamy, mixed, superactive, mesic Aridic Haplustalfs. Selected soil chemical and physical properties of the 0- to 7.6-cm soil depth for the plot area used in this study are: soil pH, 7.6; soil organic C, 12.5 g kg$^{-1}$; particulate organic C, 4.0 g kg$^{-1}$; soil electrical conductivity (1:1 water:soil ratio), 0.34 mS cm$^{-1}$; soil bulk density, 1.39 g cm$^{-3}$; sand, 403 g kg$^{-1}$; and clay, 333 g kg$^{-1}$ (Halvorson et al., 2006; Zobeck et al., 2008).

Fertilizer N sources evaluated were granular urea (46% N), liquid UAN (32% N), granular ESN (44% N), SuperU (46% N), stabilized liquid UAN with AgrotainPlus (UAN+AP), and a liquid, slow-release N source of UAN with 20% Nfusion (UAN+Nf) (22% N). All the N sources were surface-band applied by hand next to the corn row (0–10 cm from row, ~5–7 cm band width), shortly after corn emergence (18 May 2009 and 25 May 2010) and watered into the soil with 19 and 16 mm of water with a linear-move sprinkler irrigation system the day after application in 2009 and 2010, respectively. Based on the study of Holcomb et al. (2011), this amount of irrigation water was expected to reduce any $NH_3$ loss from the applied fertilizers to a very low level (<3%). An additional ESN treatment was included as a subsurface band application (ESNssb) near the corn row (~10 cm from row) at emergence. A hoe was used to make a v-shaped trench ~5 cm deep and ~5 cm wide at the top. The fertilizer was placed in the trench by hand and the trench recovered with soil using the hoe after fertilizer application. A blank treatment (no N applied) was included within the same plot area with the N sources. In addition, a check treatment that had not received N since 2000, but located in separate adjacent plots, was included in the GHG measurements to obtain background $N_2O$ levels without N fertilization. All N source treatments received the same N rate (202 kg N ha$^{-1}$). The controlled-release, polymer-coated urea, ESN, consists of urea granules coated with a polymer permeable to water that gradually releases N during the growing season, with faster releases with increasing moisture and temperatures. The stabilized urea source SuperU contains urease [N-(n-butyl)-thiophosphoric triamide] and nitrification (dicyandiamide) inhibitors that are uniformly distributed through the granule during the manufacturing process. The AgrotainPlus (registered trademark of Agrotain International, St. Louis, MO) added to UAN contains the same urease and nitrification inhibitors as SuperU. The Nfusion (registered trademark of Georgia Pacific Chemicals, LLC, Atlanta, GA) added to UAN was a slow-release, liquid N made up of slowly available urea polymers in the form of methylene urea plus triazone.

A lateral-move sprinkler irrigation system was used to apply irrigation water as needed during the growing season using Watermark soil moisture sensors (Spectrum Technologies Inc., Plainfield, IL) to estimate soil water depletion before irrigating. The N treatments were arranged in a randomized, complete-block design with three replications. Each N source plot was

3-m long by 4.6-m wide with 0.61-m-wide alleyways between N treatments. The plot area used in this study had been in a CT–CC production system from 1999–2008, with the plot area receiving 202 kg N ha$^{-1}$ in 2007 and 2008. The field operations were: strip-till to a 23-cm depth with a six-row Orthman 1tRIPr (Orthman Manufacturing Inc., Lexington, NE) on 1 Dec. 2008, after corn harvest for the 2009 study and on 31 Mar. 2010, for the 2010 study; plant corn in tilled strip on 30 Apr. 2009 and 4 May 4 2010; spray plots after crop emergence for weed control on 19 June 2009, and on 19 May 2010; and hand harvesting 24 corn plants on 28 Sept. 2009, and 30 Sept. 2010, for grain and stover yield determination at maturity but at high moisture content. Grain yield was estimated by removing the ears and shelling them to determine grain weight at 155 g kg$^{-1}$ water content. Stover yield was also determined and expressed on a dry-weight basis. Grain and stover yields were calculated using established plant stands determined from counts made in two corn rows, 11.8-m long, in adjacent plots to the N-source treatments. Herbicides were used for weed control in all treatments, resulting in the plots being relatively weed free.

Soil samples (0–7.6, 7.6–15.2, 15.2–30.5, 30.5–61.0 cm depths) were collected before spring planting and N fertilization on 10 Apr. 10 2009, and 16 Apr. 2010; during the growing season on 20 May, 3, 16, and 30 June, and 15 and 29 July 2010; and after corn harvest on 29 Nov. 2009, and 2 Nov. 2010, and analyzed for NO$_3$–N content. Spring residual soil NO$_3$–N and NH$_4$–N levels determined on air-dried soil samples are reported in Table 1. Soil NO$_3$–N levels were higher in the spring of 2009 than 2010 because of the reduced grain yield and N uptake by the corn crop in 2008 caused by a severe hail storm on 14 Aug. 2008, which defoliated (>50%) leaves from corn plants at the early kernel dent stage of growth (Halvorson et al., 2010b). The spring residual soil NO$_3$–N levels in 2010 follow a high yielding crop in 2009. In 2010, soil samples were collected from the fertilizer band to a depth of 61 cm to assess the effect of N source on soil NO$_3$–N levels early in the growing season (Table 2). At the 10 May 2010 sampling before fertilizer application, all N source plots and the check treatment had a similar level of available soil NO$_3$–N in the 0–15.2-, 0–30.5-, and 0–61-cm soil profiles. A weighted average was used to determine the soil NO$_3$–N content of the treatment using the NO$_3$–N content measured in the fertilizer band (7-cm width) and soil NO$_3$–N content of the blank treatment (no N applied) as the unfertilized area (69-cm width) across the entire 76-cm row spacing. The after-harvest soil samples for NO$_3$–N analyses (Table 3) were collected 10 to 20 cm from the corn row both years. The ESNssb treatment had a significantly higher residual NO$_3$–N content than the other N treatments at the end of the season in the 0- to 61-cm soil depth.

Measurement of the soil-atmosphere exchange of N$_2$O, CO$_2$, and CH$_4$ were made from 5 May 2009 (day of year [DOY] 125) to 22 Mar. 2010 (DOY 81), and 6 May (DOY 126) to 27 Oct. (DOY 300) 2010, following the procedures reported by Mosier et al. (2006) and Parkin and Venterea (2010). Measurements were made one to three times per week during growing seasons, midmorning of each sampling day. The general gas sampling schedule was to collect gas samples on Monday before irrigation, then on Wednesday following irrigation, and then on Thursday or Friday, with some variation in this schedule. A vented nonsteady state closed chamber technique was used (Livingston and Hutchinson, 1995). A rectangular aluminum chamber (78.6 cm by 39.3 cm by 10 cm height) with a sampling port was placed in a water channel welded onto an anchor that had been inserted 10 cm into the soil at each sampling site. Anchors were set perpendicular to the corn row (76-cm row spacing) so that the corn row and inter-row area were contained within each chamber. Anchors were installed the day of corn planting, with gas sample collection beginning 1 to 5 d later and were not removed until after corn harvest. Duplicate flux measurement sites were included within each plot for a total of six gas measurements per treatment per sampling date. The plants that had been bent over for several weeks were cut off (approximately V-8 growth stage) within each anchor on the following dates, 13 July 2009 (DOY 194) and 23 June 2010 (DOY 174). Air samples from inside the chambers were collected by syringe at 0, 15, and 30 min after the chambers were seated on the anchors. The samples were transported to the laboratory in Fort Collins, CO, where the 25-mL air samples were injected into 12-mL evacuated tubes that were sealed with butyl rubber septa (Exetainer vial from Labco Limited, High Wycombe, Buckinghamshire, UK) for analysis by gas chromatography. The gas chromatograph was a fully automated instrument (Varian model 3800, Varian Inc., Palo Alto, CA) equipped with an electron capture detector to quantify N$_2$O and thermal conductivity and

**Table 1. Spring soil NO$_3$–N and NH$_4$–N content before planting the corn crop and N fertilization in 2009 and 2010, with no significant N treatment by year interactions.**

| Year | N treatment | Soil depth | | | | | |
|------|-------------|------------|---|---|---|---|---|
| | | 0–15.2 cm | | 0–30.5 cm | | 0–61.0 cm | |
| | | NO$_3$–N | NH$_4$–N | NO$_3$–N | NH$_4$–N | NO$_3$–N | NH$_4$–N |
| | | ———————— kg N ha$^{-1}$ ———————— | | | | | |
| 2009 | Check | 12.0b† | 12.9a | 17.4b | 28.6a | 19.7b | 46.9a |
| 2009 | N source | 40.6a | 11.2a | 60.5a | 20.5b | 90.5a | 34.2b |
| 2010 | Check | 6.3b | 6.6a | 13.2b | 18.0a | 17.7b | 28.2a |
| 2010 | N source | 10.6a | 6.6a | 26.1a | 12.9b | 48.9a | 21.8b |
| 2-yr avg. | Check | 9.1a | 9.8a | 15.3b | 23.3a | 18.7b | 37.5a |
| 2-yr avg. | N source | 25.6a | 8.9a | 43.3a | 16.7a | 69.7a | 28.0a |
| 2009 | Avg. | 26.3a | 12.0a | 39.0a | 24.5a | 55.1a | 40.5a |
| 2010 | Avg. | 8.5b | 6.6b | 19.6b | 15.4b | 33.3a | 25.0b |

† Values within a column data group followed by the same letter are not significantly different at the α = 0.05 probability level.

flame ionization detectors to quantify $CO_2$ and $CH_4$ concentrations, respectively. Fluxes were calculated from the linear or nonlinear (Hutchinson and Mosier, 1981) increase in concentration (selected according to the emission pattern) in the chamber headspace with time as suggested by Livingston and Hutchinson (1995).

Estimates of daily $N_2O$, $CO_2$, and $CH_4$ emissions between sampling days were made using a linear interpolation between adjacent sampling dates. The percent $N_2O$-N emission resulting from the application of N fertilizer was calculated for each treatment after correction for emission from blank treatment (no N added). The difference between the $N_2O$-N emission with N applied and the blank treatments was divided by the quantity of fertilizer N applied and then multiplied by 100 to obtain percent.

Soil water content (0- to 10-cm depth) and soil temperature (5- to 7-cm depth) were monitored at each gas sampling event using 2 to 3 EC-TM soil moisture and temperature probes (Decagon Devices Inc., Pullman, WA) located in each replication. Water-filled pore space (WFPS) was calculated

according to the soil bulk density (measured by core method) at 0- to 10-cm depth following crop harvest and an assumed particle density of 2.65 Mg m$^{-3}$ (Linn and Doran, 1984). The date and amount of precipitation and irrigation water applied were recorded during the growing season. Precipitation was recorded by an automated weather station located within 200 m of the plot area.

Grain and stover N uptake were evaluated to provide information on the agronomic sustainability of the enhanced-efficiency fertilizers. Grain and stover N content were determined by grinding an oven-dried sample to pass a 150-μm screen and analyzing for N concentration, using an Elementar Vario Macro C-N analyzer (Elementar Americas, Inc., Mt. Laurel, NJ). Grain and stover N uptake were calculated from the N concentration and yield data.

Differences in growing season cumulative $N_2O$, $CO_2$, and $CH_4$ emissions, percentage of fertilizer N lost as $N_2O$-N, crop yields, and crop N uptake among N treatments and years were determined by analysis of variance (ANOVA), using Analytical Software Statistix9 program (Analytical Software, Tallahassee,

**Table 2. Soil NO$_3$–N levels in three depth increments from 20 May to 29 July 2010, from the N source treatments (significant N treatment × sampling day interaction).**

| N treatment† | 20 May DOY 140‡ | 3 June DOY 154 | 16 June DOY 167 | 30 June DOY 181 | 15 July DOY 196 | 29 July DOY 210 |
|---|---|---|---|---|---|---|
| | 0–15.2 cm soil depth, kg NO$_3$–N ha$^{-1}$ | | | | | |
| Urea | 9.6a§ | 31.1a | 24.2abcd | 25.1bc | 7.1a | 4.8bc |
| ESNssb | 11.7a | 13.3bc | 11.6cd | 14.2cd | 9.5a | 26.7a |
| ESN | 6.3a | 11.4c | 8.6d | 11.9cd | 6.1a | 8.2b |
| SuperU | 8.8a | 17.5bc | 18.2bcd | 17.9bcd | 15.0a | 4.9bc |
| UAN | 8.3a | 33.5a | 33.9ab | 28.9ab | 21.0a | 8.8b |
| UAN+Nf | 7.8a | 37.2a | 41.1a | 30.7ab | 16.4a | 6.1bc |
| UAN+AP | 9.2a | 24.6ab | 30.0abc | 40.7a | 16.7a | 6.3bc |
| Blank | 8.8a | 11.4c | 7.1d | 6.2d | 3.7a | 4.3bc |
| Check | 7.2a | 9.9c | 8.0d | 5.6d | 3.3a | 3.5c |
| | 0–30.5 cm soil depth, kg NO$_3$–N ha$^{-1}$ | | | | | |
| Urea | 20.5a | 40.9ab | 44.3ab | 42.5ab | 12.0a | 10.3b |
| ESNssb | 22.2a | 21.0cd | 22.1bcd | 21.3cd | 13.9a | 31.7a |
| ESN | 13.9a | 19.1d | 17.9cd | 18.3d | 9.2a | 11.8b |
| SuperU | 18.8a | 27.1cd | 31.4ab | 29.1bcd | 20.6a | 8.8b |
| UAN | 19.8a | 43.3ab | 52.1a | 38.5abc | 28.5a | 15.2ab |
| UAN+Nf | 17.8a | 47.4a | 52.7a | 44.3ab | 22.2a | 10.3b |
| UAN+AP | 20.8a | 33.7bc | 42.5ab | 50.2a | 20.4a | 9.7b |
| Blank | 20.4a | 18.8d | 16.1d | 12.0d | 6.6a | 7.5b |
| Check | 15.2a | 18.3d | 16.7cd | 11.5d | 6.7a | 7.6b |
| | 0–61.0 cm soil depth, kg NO$_3$–N ha$^{-1}$ | | | | | |
| Urea | 39.8a | 57.3ab | 65.6ab | 70.6a | 25.3bcd | 25.0a |
| ESNssb | 44.7a | 36.6de | 38.2bcd | 39.1bcd | 26.1bcd | 37.5a |
| ESN | 27.6a | 34.4cde | 33.3cd | 35.4cd | 18.6bcd | 16.0a |
| SuperU | 32.9a | 43.6bcd | 49.7abc | 52.8abc | 35.0ab | 14.3a |
| UAN | 37.9a | 60.3a | 72.5a | 58.6ab | 45.4a | 24.2a |
| UAN+Nf | 40.4a | 66.6a | 69.9a | 70.1a | 36.3ab | 16.0a |
| UAN+AP | 44.4a | 51.7abc | 59.6ab | 69.3a | 31.6abc | 14.0a |
| Blank | 44.1a | 34.0de | 31.3cd | 27.7d | 14.7cd | 11.2a |
| Check | 26.2a | 28.1e | 26.6d | 21.3d | 12.3d | 12.4a |

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ DOY, day of year.

§ Values within a columns followed by the same lowercase letter are not significantly different at $\alpha$ = 0.05 probability level.

FL). A randomized complete block ANOVA was used to evaluate N source differences within a year and a split plot ANOVA to evaluate N source differences between years with N treatment as the main effect and year as subplot. All ANOVA data were checked for normality, and when required, a logarithmic transformation was performed. After mean separation, the logarithmic-transformed means were converted back to their original scale for presentation. All statistical comparisons were made at $\alpha$ = 0.05 probability level, using the least significant difference method for mean separation.

## Results and Discussion

### Environmental Factors

Air and soil temperatures at each GHG sampling date in 2009 and 2010 are shown in Fig. 1. Both years, soil temperatures were cooler during May and early June (DOY 121–160) than the main part of the growing season, with cooler soil temperatures during May 2010 than during May 2009, but warmer temperatures starting in June through most of the growing season in 2010 than in 2009. With crop canopy closure in late June, soil temperatures rose to ~20°C and then declined start-

ing in September. Soil temperature during the December 2009 through February 2010 sampling period were generally <0°C, with an increase in soil temperature starting in early March. Air temperatures in early May were generally cooler in 2010 than in 2009.

Precipitation and irrigation amounts in 2009 and 2010 are shown in Fig. 2. Total 2009 yearly precipitation was 341 mm with May through October corn growing season totaling 259 mm. In 2009, 397 mm of irrigation water was applied to the corn crop with a growing season total (precipitation + irrigation) of 656 mm. Annual precipitation totaled 273 mm in 2010, with a May through October corn growing season total of 129 mm. In 2010, the corn received 396 mm of irrigation water, with a growing season total (precipitation + irrigation) of 525 mm.

Water-filled pore space (Fig. 3) ranged from ~65 to 80% from early May to mid-June in 2009. In 2010, WFPS ranged from ~72 to ~82% in May, then declined to a low of ~50% during June and stabilized between 60 and 70% during the rest of the growing season. During the winter months, WFPS declined to a low of ~35% in December 2009–February 2010. The WFPS tended to increase following precipitation

**Table 3. Residual soil NO$_3$–N in four soil depth increments after corn harvest in 2009 and 2010, and averages over years (no significant interaction between N treatment and years).**

| Sampling date | N treatment† | Soil depth | | | |
|---|---|---|---|---|---|
| | | 0–15.2 cm | 0–30.5 cm | 0–61.0 cm | 0–91.5 cm |
| | | ——————————— kg NO$_3$–N ha$^{-1}$ ——————————— | | | |
| 25 Nov. 2009 (DOY‡ 329) | Urea | 9.1a§ | 29.3bc | 53.1bc | 88.3ab |
| | ESNssb | 10.6a | 62.9a | 121.7a | 152.0a |
| | ESN† | 11.1a | 37.3ab | 66.5b | 83.9b |
| | SuperU† | 5.1a | 15.0bc | 34.3bc | 52.6bc |
| | UAN† | 6.2a | 19.4bc | 40.6bc | 83.0b |
| | UAN+Nf† | 5.2a | 15.0bc | 27.3bc | 39.8bc |
| | UAN+AP† | 4.6a | 13.4bc | 27.7bc | 57.8bc |
| | Blank | 2.8a | 8.4bc | 13.9c | 16.3c |
| | Check | 2.0a | 6.2c | 11.7c | 14.6c |
| 2 Nov. 2010 (DOY 306) | Urea | 10.2a | 19.4a | 28.9a | 39.1a |
| | ESNssb | 36.0a | 53.4a | 64.4a | 73.6a |
| | ESN | 14.6a | 24.6a | 34.5a | 39.8a |
| | SuperU | 14.1a | 32.8a | 53.1a | 66.1a |
| | UAN | 14.7a | 26.0a | 35.7a | 44.2a |
| | UAN+Nf | 18.1a | 30.2a | 42.2a | 50.2a |
| | UAN+AP | 17.3a | 28.1a | 40.9a | 55.5a |
| | Blank | 5.4a | 9.2a | 12.7a | 15.9a |
| | Check | 6.1a | 9.6a | 14.0a | 16.2a |
| Avg. 2009 and 2010 | Urea | 9.7b | 24.3b | 41.0b | 63.7ab |
| | ESNssb | 22.6a | 63.4a | 101.6a | 118.7a |
| | ESN | 13.7ab | 29.5ab | 49.0ab | 63.4ab |
| | SuperU | 9.6b | 23.9b | 43.7b | 59.4b |
| | UAN | 10.4ab | 22.7b | 38.2b | 63.6ab |
| | UAN+Nf | 11.6ab | 22.6b | 34.7b | 45.0b |
| | UAN+AP | 10.9ab | 20.7b | 34.3b | 56.5b |
| | Blank | 4.1c | 8.8c | 13.3c | 16.1c |
| | Check | 4.1c | 7.9c | 12.9c | 15.4c |

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ DOY = day of year.

§ Values within a columns followed by the same lowercase letter are not significantly different at $\alpha$ = 0.05 probability level.
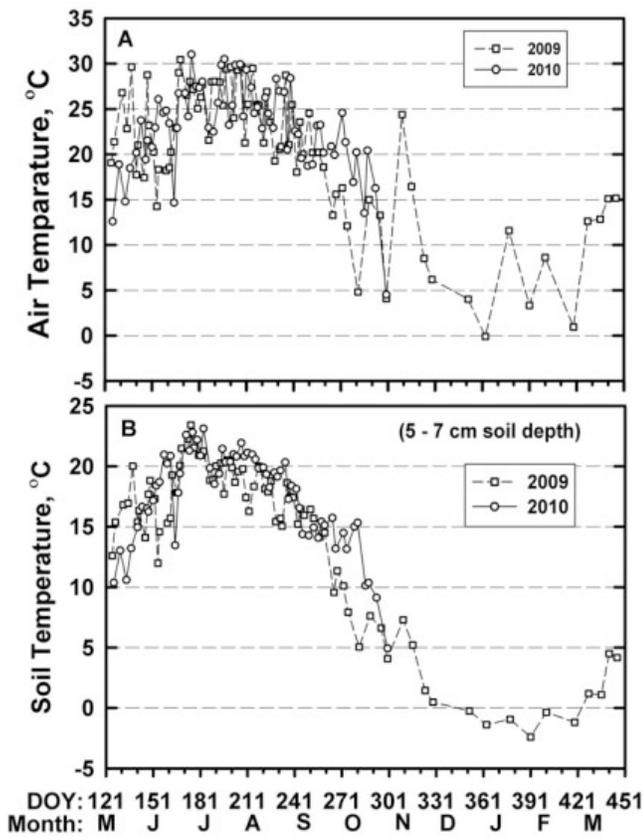
**Fig. 1. Air (A) and soil temperature (B) at about the 5- to 7-cm depth measured at the time of gas flux measurement in 2009 and 2010.**



**Fig. 3. Water-filled pore space in the 0- to 10-cm soil depth from 5 May 2009 to 22 Mar. 2010 and 6 May 2010 through 31 Oct. 2010.**

and irrigation events (Fig. 2) and averaged 67.8 and 65.1% during the 2009 and 2010 growing seasons (May–September), respectively.

## Nitrous Oxide Fluxes

Nitrous oxide fluxes increased within days following the application of all N sources except for ESN, which had a delayed release of $N_2O$ in 2009 (Fig. 4) and 2010 (Fig. 5). Nitrous oxide fluxes were highest the first 30 d following N fertilization with
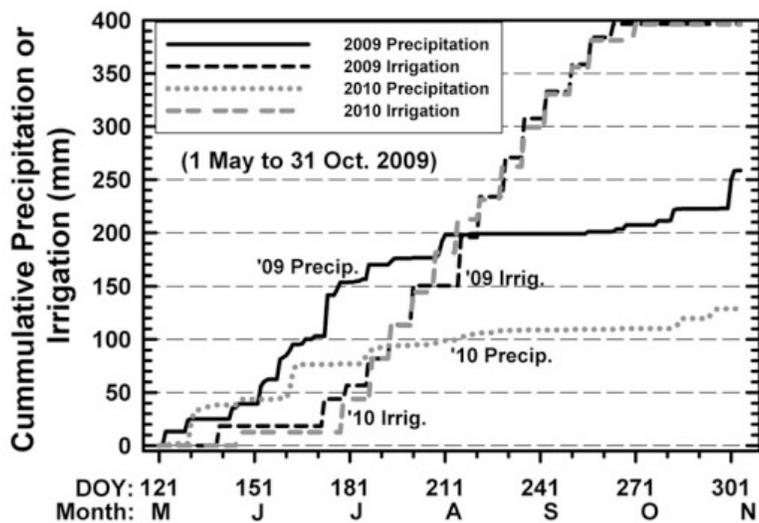


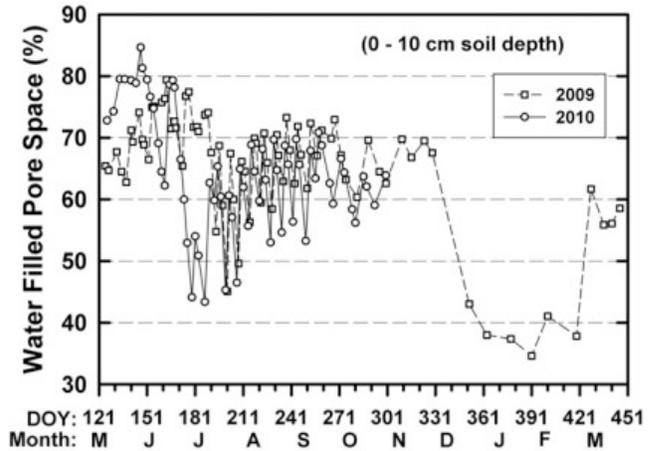**Fig. 2. Cumulative growing season precipitation and irrigation amounts applied in 2009 and 2010.**

urea and UAN when WFPS was highest and then declined to near background levels in ~45 d. Similarly, $N_2O$-N fluxes from SuperU increased within days following application but were of a smaller magnitude than for urea and UAN, then decreasing down to background levels in ~45 d both years. This trend corresponds to the trend of soil $NO_3$–N levels being lower for SuperU in 2010 in the 0- to 15.2- and 0- to 30.5-cm soil depths during June than urea and all UAN treatments (Table 2). Also, $N_2O$-N flux peaks resulting from UAN+Nfusion and UAN+AgrotainPlus application occurred within days of application but were of a much smaller magnitude that those observed for UAN alone, even though the measured soil $NO_3$–N levels were similar to UAN (Table 2). Nitrous oxide fluxes from ESN and ESNssb followed a different pattern, remaining low until mid-June when $N_2O$-N fluxes started to increase both years (Fig. 4 and 5). In 2010, the soil $NO_3$–N levels for the ESN treatments were generally less than for the other N sources during the early part of the growing season following N application. On 29 July, the ESNssb treatment had higher soil $NO_3$–N levels than the other N treatments (Table 2). The $N_2O$ flux peaks from the ESN treatments during the growing season were greater in 2010 (Fig. 5) than in 2009 (Fig. 4), possibly due to a faster release of the urea N from the polymer-coated granule because of higher soil temperatures in 2010 than in 2009 (Fig. 1). Peaks from ESN application tended to be higher than those from the other N sources during mid-June through August but tended to be smaller and of shorter duration than the peaks observed just after urea or UAN application. The late-season $N_2O$-N fluxes from the ESN are consistent with the results reported by Halvorson et al. (2010b). The rapid increase in $N_2O$ emissions following N application is consistent with work of Omonode et al. (2011) who reported that 50% of the $N_2O$ emissions occurred shortly after N application, regardless of tillage or crop rotation practices, and with previous work done at this site by Mosier et al. (2006) and Halvorson et al. (2008, 2010a,b).

In 2009, we were able to collect $N_2O$ flux measurements during the noncrop period (1 Oct. 2009–22 Mar. 2010). Nitrous oxide fluxes remained near
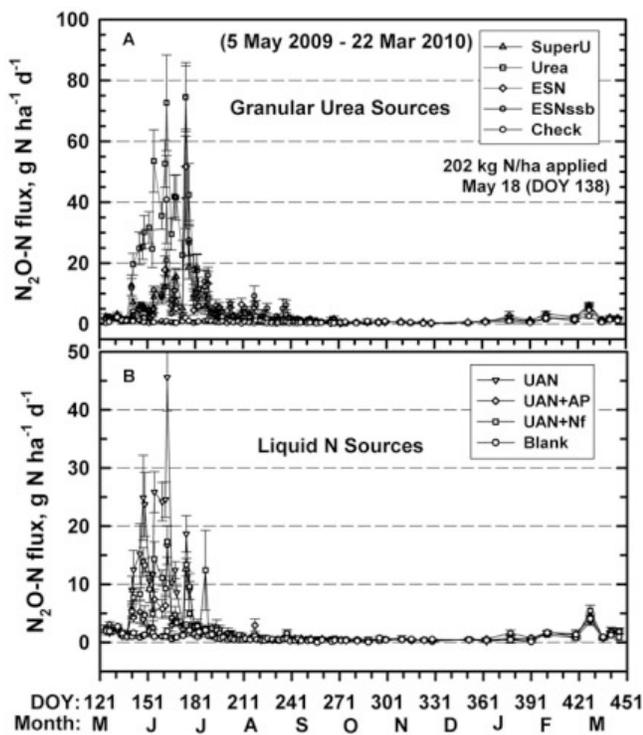
**Fig. 4. Daily N₂O-N fluxes with standard error bars at each sampling date in 2009 for (A) SuperU, urea, ESN, ESN subsurface band (ESNssb), and check; and (B) urea-ammonium nitrate (UAN), UAN+AgrotainPlus (AP), UAN+Nfusion (Nf), and blank. Note the different scales on Y axis.**



**Fig. 5. Daily N₂O-N fluxes with standard error bars at each sampling date in 2010 for (A) SuperU, urea, ESN, ESN subsurface band (ESNssb), and check; and (B) urea-ammonium nitrate (UAN), UAN+AgrotainPlus (AP), UAN+Nfusion (Nf), and blank. Note the different scales on Y axis.**

background levels for the entire period for all N treatments, with a slight rise in N$_2$O emissions on 4 Mar. 2010, as the frozen soil had thawed and soil temperatures increased, with a decline to background levels at the 12 Mar. sampling date. The slight increase in N$_2$O emissions as the soil thawed out is consistent with the observations of others who reported increased N$_2$O fluxes at spring thaw (Hao et al., 2001; Dusenbury et al., 2008). Average N$_2$O-N emissions (174 d) for the noncrop period were: 1.44a, 1.23ab, 1.18ab, 1.13bc, 0.99bcd, 0.88cd, 0.87cd, 0.80d, and 0.79d g N ha$^{-1}$d$^{-1}$ for ESNssb, ESN, SuperU, urea, UAN+AP, UAN+Nf, check, UAN, and blank, respectively, with significant differences indicated by lowercase letters following the daily emission value. The ESNssb treatment had the highest daily noncrop period emissions and the blank (no N applied) had the lowest emissions. The ESNssb treatment also had the highest level of residual soil NO$_3$–N in late November 2009 (Table 3), which probably accounts for the slightly higher N$_2$O emissions during the noncrop period. Nitrification was probably the dominant pathway of soil N$_2$O loss from applied N fertilizer from this ST, irrigated system based on WFPS being generally <70% both years, except for a short period in early 2010 when WFPS was ~80% before N fertilization (Linn and Doran, 1984). The slightly elevated level of residual soil NO$_3$–N at the end of the growing season with the ESNssb treatment is consistent with the observations of Venterea et al. (2011a) who reported slightly elevated residual soil N with the polymer-coated urea than with conventional urea in Minnesota.

Cumulative daily N$_2$O-N fluxes during the corn growing season are shown in Fig. 6 for 2009 and Fig. 7 for 2010. A rapid rise in cumulative daily flux levels for urea and UAN
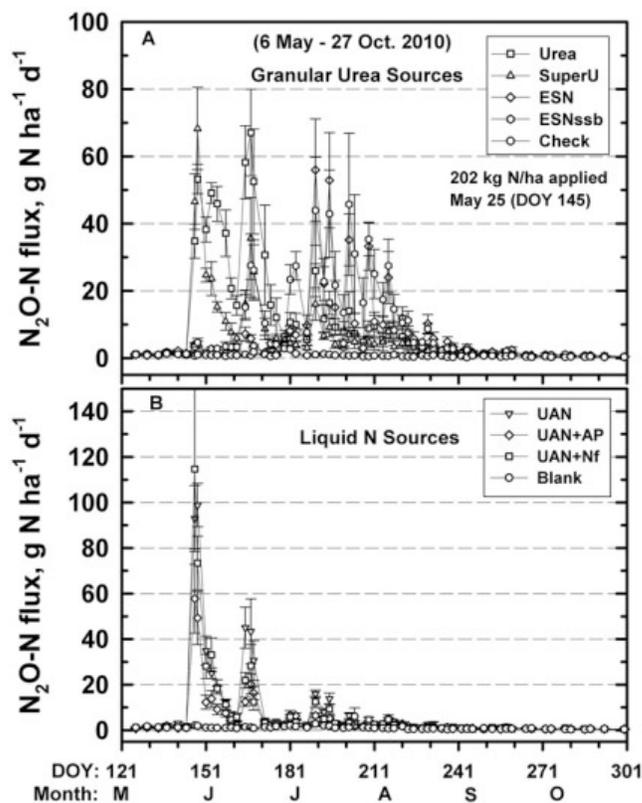
was very apparent both years following N application, with SuperU, UAN+Nfusion, and UAN+AgrotainPlus also showing rapid rises in cumulative N$_2$O emissions immediately following N application in 2010. Cumulative growing season emissions were greater in 2010 than 2009 for all N treatments, except for urea, which was similar both years but followed similar relative emission patterns both years. The rise in cumulative daily N$_2$O-N flux was slower for all enhanced-efficiency N sources than for urea and UAN both years. The delayed release of N$_2$O-N from ESN until about mid-June was very prominent in 2010. The N$_2$O emissions from the blank (no N applied) treatments that had received 202 kg N ha$^{-1}$ in previous years was very similar to that from the check treatment that had not had any N applied since 1999. The residual soil NO$_3$–N (Table 1) in the 0- to 15.2-, 0- to 30.5-, and 0- to 61-cm depths were significantly greater in the N source plot area where the blank treatment resided than in the check treatment located in an adjacent plot. Although the residual soil NO$_3$–N was greater in the blank plot area than in the check plot area before corn planting, we did not observe a significant difference (Table 4) in growing season N$_2$O emissions between the blank and check treatments. Dobbie et al. (1999) reported a critical soil NO$_3$–N concentration of 5 mg NO$_3$–N kg$^{-1}$ below which N$_2$O emissions may be much reduced, even at high levels of WFPS. This observation has been supported by other researchers (Izaurralde et al., 2004; Dusenbury et al., 2008). In this study, the difference in NO$_3$–N levels in the 0- to 15.2-cm soil depth had disappeared by 20 May 2010 (DOY 140), between the check
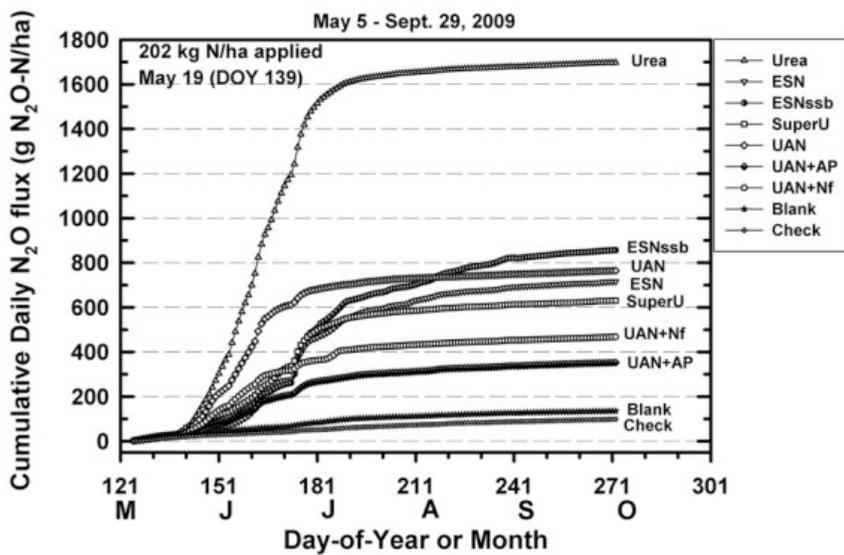
**Fig. 6. Cumulative daily $N_2O$-N emissions during the 2009 growing seasons for each N treatment: urea, urea-ammonium nitrate (UAN), ESN, ESN subsurface band (ESNssb), SuperU, UAN+Nfusion (Nf), UAN+AgrotainPlus (AP), blank, and check.**



**Fig. 7. Cumulative daily $N_2O$-N emissions during the 2010 growing seasons for each N treatment: urea, urea-ammonium nitrate (UAN), ESN, ESN subsurface band (ESNssb), SuperU, UAN+Nfusion (Nf), UAN+AgrotainPlus (AP), blank, and check.**
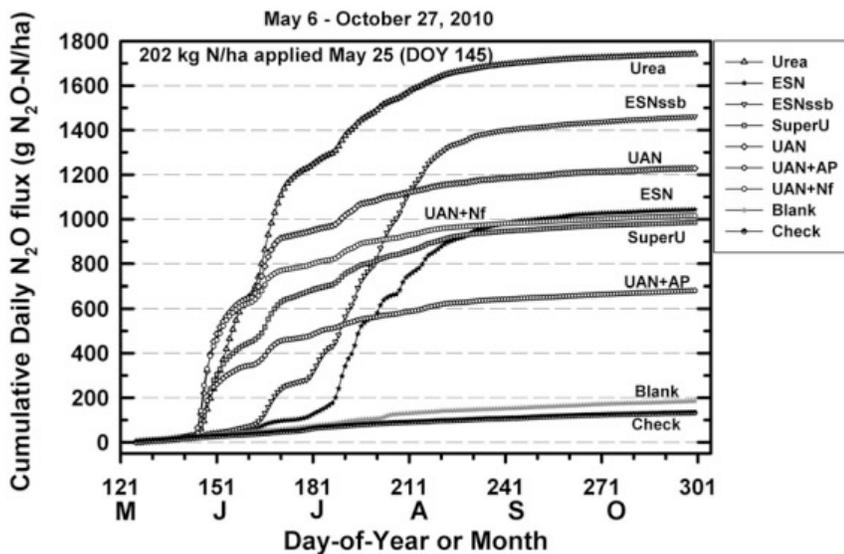
and blank treatments. A soil $NO_3$–N concentration of 5 mg $NO_3$–N $kg^{-1}$ would equate to ~11 kg $NO_3$–N $ha^{-1}$ in this study, with the blank and check treatments generally having lower $NO_3$–N levels than 11 kg $NO_3$–N $ha^{-1}$ during the growing season. This may help explain why there was little difference in $N_2O$ emissions between the blank and check during the growing season. This observation between the blank and check treatments was observed both years. This would tend to indicate in our system that the fresh application of N fertilizer was stimulating microbial activity and the nitrification process resulting in $N_2O$ loss from the N fertilizer applied. The fact that WFPS (Fig. 3) was generally <70% most of the growing season would support the theory that nitrification is the main pathway of $N_2O$ loss at this location (Linn and Doran, 1984).

Nitrous oxide emissions for the two growing seasons (5 May to 29 Sept. 2009 and 6 May to 29 Sept. 2010) are reported in Table 4, with a significant N source × year interaction. This interaction probably resulted from ESNssb, SuperU, UAN, UAN+Nfusion, and UAN+AgrotainPlus having significantly greater $N_2O$ emissions in 2010 than in 2009 but no difference between years for urea, ESN, blank, and the check treatments. Averaged over both years, growing season $N_2O$-N emissions from all enhanced-efficiency N fertilizers were significantly lower than granular urea, including UAN. The ESNssb treatment had significantly higher $N_2O$ emissions than the UAN+Nfusion, UAN+AgrotainPlus, blank, and check treatments. The UAN+Nfusion and UAN+AgrotainPlus treatments had lower $N_2O$ emissions than UAN. The blank and check treatments had the lowest level of growing season $N_2O$-N emissions and were not significantly different. Averaged over N sources, growing season $N_2O$ emissions were lower in 2009 than in 2010. The higher WFPS in 2010 during May through mid-June than in 2009 (Fig. 3) may have contributed to the yearly difference, with some denitrification possibly contributing to the increased $N_2O$ loss. The differences between years is consistent with the observations of Mosier et al. (2006) and Halvorson et al. (2008) who reported yearly differences for this site.

Compared with granular urea (averaged over years), UAN+AgrotainPlus reduced $N_2O$-N emissions 70%, UAN+Nfusion 57%, SuperU 53%, ESN 49%, UAN 42%, and ESNssb 33% in this ST production system. Compared with liquid UAN, UAN+AgrotainPlus reduced $N_2O$-N emissions 49%, UAN+Nfusion 26%, SuperU 19%, and ESN 12%. These results are thus in good agreement with Halvorson et al. (2010a,b) who showed substantial reductions in $N_2O$-N emissions with the use of enhanced-efficiency N fertilizers in NT systems.

The $N_2O$-N emission losses as a percentage of fertilizer N applied are reported in Table 4, with no significant interaction between N source and year. The $N_2O$-N loss was significantly higher in 2010 than in 2009, with N sources having significant differences in $N_2O$-N loss. All N sources had significantly lower $N_2O$-N emission losses than granular urea. This result indicates that the potential for reduction of $N_2O$-N emissions with the use of controlled-release, slow-release, and stabilized N fertilizer sources in ST systems is substantial. The calculations above show that the fertilizer-induced component of $N_2O$-N emissions could be reduced up to 70% by using enhanced-efficiency N sources in semiarid, irrigated cropping

**Table 4. Cumulative growing season N₂O-N flux (5 or 6 May–29 Sept.) and fertilizer-induced N₂O-N emissions as a percentage of fertilizer N applied (significant N treatment × year interaction for growing season N₂O emission only).**

| N treatment† | Cumulative growing season N₂O-N emissions | | | N₂O-N emissions as % of fertilizer N applied | | |
|---|---|---|---|---|---|---|
| | 2009 | 2010 | Avg. | 2009 | 2010 | Avg. |
| | ——————— N₂O-N, g N ha⁻¹ ——————— | | | ——————— % ——————— | | |
| Urea | 1698a‡ | 1726a | 1712a | 0.77a | 0.77a | 0.77a |
| ESNssb | 856cde | 1439ab | 1147b | 0.36b | 0.63b | 0.49b |
| ESN | 716def | 1028bcde | 872bc | 0.29c | 0.42bc | 0.36cd |
| SuperU | 631ef | 972bcd | 801bc | 0.25cd | 0.40bc | 0.32cd |
| UAN | 765de | 1214abc | 989b | 0.31bc | 0.52b | 0.41bc |
| UAN+Nfusion | 468fg | 1001bcd | 734c | 0.16de | 0.41bc | 0.29de |
| UAN+AgrotainPlus | 352g | 665ef | 509d | 0.11e | 0.24c | 0.18e |
| Blank (no N added) | 136hi | 172h | 154e | – | – | |
| Check (no N added) | 99i | 123hi | 111e | – | – | |
| Avg. | 636B§ | 927A | | 0.34B | 0.51A | |

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea–ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a column followed by the same lowercase letter are not significantly different at $\alpha$ = 0.05 probability level or across 2009 and 2010 columns for N₂O growing season emissions.

§ Values within a row followed by the same uppercase letter are not significantly different at $\alpha$ = 0.05 probability level.

systems. The degree of reduction may vary strongly, depending on cropping system, tillage management, and site-specific conditions as pointed out by Halvorson et al. (2010a). The growing season N₂O-N emissions from the application of a unit of the enhanced-efficiency N fertilizers used in this study were considerably lower (<0.5%) than the default 1% from Tier I methodology of De Klein et al. (2006) used to estimate yearly N₂O-N emissions resulting from N fertilizer application. This indicates the need for source and site-specific N₂O emission data (Adviento-Borbe et al., 2007; Bouwman et al., 2002; Rochette et al., 2008; Snyder et al., 2009). The results presented here may indicate that irrigated soils under semiarid conditions have relatively low N₂O-N losses, provided irrigation is well managed to avoid water-logged conditions and potential for denitrification. In only 1 out of 9 yr have N₂O-N emissions exceeded 1% of N applied at this site (Mosier et al., 2006; Halvorson et al., 2008, 2010a,b), with 1 yr (2003) having very wet soil conditions at fertilization, planting, and during the early growing season.

## Carbon Dioxide and Methane Emissions

Growing season CO₂–C emissions varied with N treatment and year, with no significant N source × year interaction. The check with no N applied had higher growing season CO₂–C emissions (2803 kg C ha⁻¹) than SuperU (2434 kg C ha⁻¹), blank (2386 kg C ha⁻¹), Nfusion (2347 kg C ha⁻¹), ESN (2294 kg C ha⁻¹), and urea (2291 kg C ha⁻¹). Differences among N sources in CO₂ emissions were unexpected, with no logical explanation for this difference available. Averaged over years, daily growing season CO₂–C emissions (148 d) did not vary with N treatment, averaging 16.8 kg C ha⁻¹ d⁻¹. The average daily CO₂–C emissions in 2010 (17.4 kg C ha⁻¹ d⁻¹) was greater than in 2009 (16.1 kg C ha⁻¹ d⁻¹). In 2009 during the noncrop period (30 Sept. 2009–22 Mar. 2010), there was no significant difference in daily CO₂–C emissions among N treatments with an average daily emission of 2.4 kg C ha⁻¹d⁻¹.

Growing season daily CH₄–C emissions (148 d) did not vary among N treatments (0.34 g C ha⁻¹ d⁻¹), with no signifi-

cant N source × year interaction. Daily CH₄–C emissions were greater in 2010 (0.41 g C ha⁻¹d⁻¹) than in 2009 (0.28 g C ha⁻¹ d⁻¹). Daily CH₄–C emissions for the 174 d noncrop period (30 Sept. 2009 to 22 Mar. 2010) did not vary with N treatment and averaged 0.25 g C ha⁻¹d⁻¹.

## Corn Grain and Stover Yield and Nitrogen Uptake

There was a significant increase in grain yield and grain N uptake with application of 202 kg N ha⁻¹ when compared with the blank and check treatments both years (Table 5), with a significant N treatment × year interaction. Both years, there was no significant grain yield differences among N sources, however, grain yields with N application were greater in 2010 than in 2009 for all N source treatments but lower in 2010 than 2009 for the blank and check treatments, which resulted in significant interaction. Cahill et al. (2010), Halvorson et al. (2010b), Nelson et al. (2009), and Venterea et al. (2011b) also reported no or small corn yield differences among N sources applied at similar N rates. Similarly, grain N uptake (Table 5) for the blank and check treatments were lower in 2010 than in 2009, with no differences in N uptake between N sources in 2009 or 2010, thus causing significant interaction. Averaged over both years, enhanced-efficiency fertilizers did not affect grain yields, with all alternative N sources not significantly different from urea and UAN. The grain yield of the blank and check treatments averaged (2 yr) 70 and 46% of the highest grain yield, respectively. The check treatment had not been fertilized since 1999, so the resulting yield is primarily from mineralization of soil organic matter plus N applied with the irrigation water (14 and 25 kg N ha⁻¹ in 2009 and 2010, respectively). Based on the grain yield and N uptake data over both years, the enhanced-efficiency fertilizers did not have any grain yield advantage over granular urea or liquid UAN in our study.

Stover yields did not vary among N sources with a significant N treatment × year interaction (Table 6). The significantly lower stover yields in 2010 compared with 2009 for the blank and check treatments probably caused the interaction. Stover yields with N application were significantly greater than with

no N applied, with the check treatment being significantly lower than the blank treatment (Table 6). Stover yields did not vary with year. Stover N uptake was greater with urea than with UAN+AgrotainPlus, with no other differences among N sources (Table 6). Stover N uptake was greater with N application than without N application, with the blank having a greater N uptake than the check treatment. There was no difference in N uptake between years.

## Nitrous Oxide Emissions as a Function of Grain Yield and Nitrogen Uptake

Van Groenigen et al. (2010) suggested that $N_2O$ emissions need to be assessed as a function of crop N uptake and grain yield to provide an agronomic assessment of $N_2O$ emissions. They also pointed out that to minimize $N_2O$ emissions and maintain or increase crop yield, N uptake by the crop must be maximized. Nitrous oxide emissions per megagram of grain

yield for each N treatment in this study are presented in Table 7. When analyzed over both years, there was no significant N treatment × year interaction. Averaged over years, all enhanced-efficiency N sources, including UAN, had lower $N_2O$-N emission levels per megagram of grain yield than urea. The ESNssb treatments had greater $N_2O$ emissions per megagram grain than UAN+Nfusion, UAN+AgrotainPlus, blank, and check treatments. The UAN+AgrotainPlus had lower $N_2O$ emissions per megagram grain than UAN. The blank and check treatments had the lowest level of $N_2O$ emissions per megagram grain, but these are not economically sustainable management practices (Archer et al., 2008; Archer and Halvorson, 2010). The $N_2O$ emissions per megagram grain were slightly higher in 2010 than in 2009, consistent with the higher level of $N_2O$ emissions in 2010 than in 2009 (Table 7). These data show that the enhanced efficiency fertilizers have potential to reduce

**Table 5. Grain yield (at 155 g kg⁻¹ water content) and grain N uptake for each N treatment in 2009 and 2010, and averages for both years (significant N treatment × year interactions).**

| N treatment† | Grain yield | | | Grain N uptake | | |
|---|---|---|---|---|---|---|
| | 2009 | 2010 | Avg. | 2009 | 2010 | Avg. |
| | ———— Mg ha⁻¹ ———— | | | ———— kg N ha⁻¹ ———— | | |
| Urea | 13.11bc‡ | 15.44a | 14.28a | 142ab | 138ab | 140a |
| ESNssb | 13.76b | 15.79a | 14.78a | 154a | 157a | 155a |
| ESN | 13.56bc | 15.43a | 14.50a | 147a | 139ab | 143a |
| SuperU | 13.70b | 16.24a | 14.97a | 150a | 147a | 149a |
| UAN | 12.97bc | 16.64a | 14.81a | 141ab | 150a | 145a |
| UAN+Nfusion | 13.21bc | 16.05a | 14.63a | 145a | 135ab | 140a |
| UAN+AgrotainPlus | 13.22bc | 15.33a | 14.27a | 144a | 136ab | 140a |
| Blank (no N added) | 12.11c | 8.80d | 10.45b | 120b | 59c | 90b |
| Check (no N added) | 8.43d | 5.47e | 6.95c | 61c | 43c | 52c |
| Avg. | 12.68B§ | 13.91A | | 134A | 123B | |

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a column followed by the same lowercase letter are not significantly different at $\alpha$ = 0.05 probability level or across 2009 and 2010 columns for grain yield and grain N uptake interactions.

§ Values within a row followed by the same uppercase letter are not significantly different at $\alpha$ = 0.05 probability level.

**Table 6. Stover yield (dry weight basis) and N uptake for each N treatment in 2009 and 2010, and averages for both years (significant N treatment × year interaction for stover yield only).**

| N treatment† | Stover yield | | | Stover N uptake | | |
|---|---|---|---|---|---|---|
| | 2009 | 2010 | Avg. | 2009 | 2010 | Avg. |
| | ———— Mg ha⁻¹ ———— | | | ———— kg N ha⁻¹ ———— | | |
| Urea | 9.39a‡ | 9.07ab | 9.23a | 60a | 60a | 60a |
| ESNssb | 9.44a | 9.45a | 9.44a | 63a | 56a | 59ab |
| ESN | 9.28a | 9.07ab | 9.17a | 58a | 60a | 59ab |
| SuperU | 9.30a | 9.50a | 9.40a | 55ab | 57a | 56ab |
| UAN | 8.80ab | 9.71a | 9.26a | 50ab | 58a | 54ab |
| UAN+Nfusion | 8.58ab | 9.27ab | 8.93a | 51ab | 59a | 55ab |
| UAN+AgrotainPlus | 8.58ab | 9.14ab | 8.86a | 51ab | 51a | 51b |
| Blank (no N added) | 8.16b | 5.92c | 7.04b | 44b | 25b | 35c |
| Check (no N added) | 6.45c | 4.19d | 5.32c | 27c | 18b | 23d |
| Avg. | 8.67A§ | 8.37A | | 51A | 49A | |

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a column followed by the same lowercase letter are not significantly different at $\alpha$ = 0.05 probability level or across 2009 and 2010 columns for stover yield interaction.

§ Values within a row followed by the same uppercase letter are not significantly different at $\alpha$ = 0.05 probability level.

$N_2O$-N emissions per unit of grain production at this semiarid, irrigated corn production site in the Central Great Plains.

Following the examples of Venterea et al. (2011b) and Van Groenigen et al. (2010) for evaluating agronomic N use efficiencies, we also expressed growing season $N_2O$ emissions on a per kilogram of grain and total aboveground biomass (grain + stover) N uptake basis for each N treatment. Growing season emissions per unit of grain N uptake are reported in Table 7. Urea had significantly higher $N_2O$-N emissions per kilogram grain N uptake than the enhanced-efficiency N sources, including UAN. The UAN+AgrotainPlus had significantly lower emissions per kilogram of grain N uptake than UAN and was not significantly different from the blank and check treatments receiving no N fertilizer. The N treatment × year interaction was not significant. Consistent with the grain N uptake data (Table 5), grams $N_2O$-N emissions per kilogram grain N uptake were greater in 2010 (6.9) than in 2009 (4.5). These emission levels were similar to the range (4.0–10.7 g $N_2O$-N $kg^{-1}$ grain N) reported by Venterea et al. (2011b) in Minnesota. Izaurralde et al. (2004) similarly reported a lower $N_2O$ emission loss as a percentage of grain N harvested for a zero N applied treatment than for a high N application treatment in a spring wheat (*Triticum aestivum* L.) system.

Growing season $N_2O$-N emissions per kilogram of total biomass N uptake (Table 7) showed the same trends in treatment differences as observed for grain N uptake above. Urea had the highest level of $N_2O$-N emissions per kilogram total biomass N uptake with UAN+AgrotainPlus, blank, and check treatments being the lowest. Based on an N surplus analysis (N fertilizer applied – total aboveground biomass N uptake), the N surplus averaged over both years in this study was 1.2 kg N $ha^{-1}$, which would make this an $N_2O$-efficient cropping system as projected by the meta-analysis of Van Groenigen et al. (2010). Averaged over the 2 yr, the N fertilizer recovery efficiency ([total biomass N uptake with N applied – total biomass N uptake with no N applied]/N fertilizer applied) (Noellsch et al., 2009) was 38%, with no differences among N sources but significant yearly differences—18% in 2009 and 57% in 2010, when using the blank as the no N applied treatment. Using the check as the no N applied treatment resulted in a 73% N fertilizer recovery efficiency, with significant yearly differences, 56% in 2009 and 90% in 2010. The N fertilizer recovery efficiency was lower in 2009 as a result of the relatively high yield and N uptake of the blank treatment in 2009 compared with 2010. The higher yield and N uptake of the blank and check treatments in 2009 was probably due to the higher level of residual soil $NO_3$–N levels (Table 1) in 2009 than 2010. These N fertilizer recovery efficiencies are similar to those reported by Venterea et al. (2011b) and Noellsch et al. (2009).

## Conclusions

Controlled-release, slow-release, and stabilized N sources reduced $N_2O$-N emissions from an irrigated, ST, CC cropping system when compared with granular urea. Nitrous oxide fluxes resulting from urea, UAN, SuperU, UAN+Nfusion, and UAN+AgrotainPlus applications peaked within days after application, whereas $N_2O$ flux peaks from ESN and ESNssb occurred 4 to 6 wk after application but with flux peaks generally of lower magnitude than with conventional urea. All enhanced-efficiency fertilizers and UAN reduced growing season $N_2O$ emissions when compared with urea, and UAN+Nfusion and UAN+AgrotainPlus did so in comparison to UAN. Nitrification was probably the main pathway of soil $N_2O$ loss from applied N fertilizer from this ST, irrigated system throughout most of the growing season, except for possibly some loss due to denitrification in early May 2010 when WFPS reached 80% for a short period. Growing season N losses as $N_2O$-N were consistently <0.5% of N applied for all enhanced-efficiency N sources, including UAN, with urea having a loss of <0.8%. Expressing $N_2O$ emissions as a function of grain yield and N uptake showed greater agronomic N use efficiency for the enhanced-efficiency N fertilizers than for urea. This study shows that N source can affect $N_2O$-N emissions following N fertilizer application. Choice of N source can be a valid management alternative for reducing $N_2O$ emissions to the environment in the semiarid western United States. Additional work is needed to verify the effectiveness of these fertilizer sources in reducing $N_2O$ emissions in other rainfed and irrigated cropping systems, especially in humid areas with large amounts of untimely spring rainfall, which can contribute to $N_2O$ losses through denitrification.

## Acknowledgments

Table 7. Average (2009–2010) growing season $N_2O$-N emissions as a function of corn grain yield, grain N uptake, and total aboveground N uptake (grain + stover) for each N Treatment (no significant N treatment × year interaction).

| N treatment† | g $N_2O$-N $Mg^{-1}$ grain yield | g $N_2O$-N $kg^{-1}$ grain N uptake | g $N_2O$-N $kg^{-1}$ total N uptake |
|---|---|---|---|
| Urea | 121a‡ | 12.2a | 8.5a |
| ESNssb | 78b | 7.3b | 5.3b |
| ESN | 61bc | 6.1bc | 4.3bc |
| SuperU | 54bcd | 5.6bc | 4.0bcd |
| UAN | 66bc | 6.8b | 5.0bc |
| UAN+Nfusion | 49cd | 5.3bc | 3.8cd |
| UAN+AgrotainPlus | 36de | 3.8cd | 2.7de |
| Blank (no N added) | 15e | 2.2d | 1.6e |
| Check (no N added) | 17e | 2.0d | 1.4e |
| Avg. 2009 | 48B§ | 4.5B | 3.2B |
| Avg. 2010 | 62A | 6.9A | 4.9A |

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a columns followed by the same lowercase letter are not significantly different at α = 0.05 probability level.

§ Values within a column followed by the same uppercase letter are not significantly different at α = 0.05 probability level.

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