

# Greenhouse Gas Emissions from an Irrigated Dairy Forage Rotation as Influenced by Fertilizer and Manure Applications

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Information is needed regarding the effect of N source on greenhouse gas (GHG) emissions from irrigated semiarid agricultural soils. We report  $N_2O$ ,  $CO_2$ , and  $CH_4$  emissions from a silage corn (*Zea mays* L.) (2013)–barley (*Hordeum vulgare* L.) (2014)–alfalfa (*Medicago sativa* L.) (2015) rotation under conventional tillage and sprinkler irrigation. We evaluated the effectiveness of an enhanced-efficiency fertilizer (SuperU, a stabilized granular urea with urease and nitrification inhibitors) to reduce  $N_2O$  emissions compared with granular urea and to determine GHG emissions from fall-applied dairy manure or composted dairy manure and spring-applied dairy manure. Nitrogen was applied during the first 2 yr of the study. SuperU plots emitted 53% less  $N_2O$  than urea with corn, whereas no emission reductions occurred in 2014 with barley. The  $N_2O$ -N emission losses as a percentage of total N applied were 0.21 and 0.04% for urea and SuperU in 2013, respectively, with losses of 0.05% from both urea fertilizers in 2014. On average,  $N_2O$  fluxes from fall and spring manure were statistically similar and greater than the other N treatments in 2014 and a lasting manure treatment effect on emissions occurred under alfalfa. Carbon dioxide fluxes were greatest from fall- and spring-applied manure during the first 2 yr. Methane fluxes were negative, indicating microbial oxidation, and no differences occurred among the treatments. Corn, barley, and alfalfa yields were similar among all N treatments. This work demonstrates that SuperU can reduce  $N_2O$  emissions from irrigated cropping systems in the semiarid western United States without affecting yields.

Abbreviations: DOY, day of the year; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; VWC, volumetric water content.

Fertilization and irrigation make intensive agricultural production possible in many arid regions. Although application of N to soils is associated with increased  $N_2O$  emissions, very few reports have addressed the effects of fertilizer and manure applications on  $N_2O$  emissions from irrigated cropping systems in semiarid regions (Haile-Mariam et al., 2008; Halvorson et al., 2016). According to the USEPA (2016), agricultural soil management (i.e., fertilizer application and other cropping practices) accounts for 4.6% of total US GHG emissions and 77% of total US  $N_2O$  emissions from anthropogenic activities. Nitrous oxide is produced naturally in soils through nitrification and denitrification processes (Robertson and Groffman, 2007). As a GHG,  $N_2O$  has a global warming potential 298 times that of  $CO_2$  over a 100-yr timescale (Solomon et al., 2007). As a result of continuing concerns over impacts from agricultural GHGs on global climate change, there is a need for improved emissions inventories (Eve et al., 2014; USEPA, 2016). Currently, the Intergovernmental Panel on Climate Change (IPCC) methodology for determining direct  $N_2O$  emissions from fertilizer (i.e.,

## Core Ideas

- Urea formulated with urease and nitrification inhibitors can reduce  $N_2O$  emissions.
- Nitrous oxide-N emission losses as a percentage of total N applied were  $\leq 0.21\%$ .
- Timing of manure application did not affect  $N_2O$ ,  $CO_2$ , and  $CH_4$  fluxes.
- Soil was a  $CH_4$  sink and emissions were not influenced by N source.

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synthetic, manure, crop residues) applied to agricultural soils uses a Tier 1 emissions factor of 1% of the applied N (Eggleston et al., 2006).

Despite the fact that  $N_2O$ -N losses from agricultural soils are relatively small ( $\leq 6.8\%$ ) compared to N inputs (Eichner, 1990), efforts to mitigate  $N_2O$  losses are of significant interest because worldwide use of N fertilizer is expected to increase and  $N_2O$  is also an ozone-depleting substance (Venterea et al., 2012). To date, there are a number of potentially useful  $N_2O$  mitigation strategies (Snyder et al., 2009). One promising strategy to mitigate direct emissions is the use of enhanced-efficiency N fertilizers with urease and nitrification inhibitors (Halvorson et al., 2014). In a semiarid irrigated cropping system located in Colorado, SuperU (a stabilized urea source with urease [*N*-(*n*-butyl)-thiophosphoric triamide] and nitrification inhibitors;(2-cyanoguanidine) Koch Agronomic Services, LLC., Wichita, KS) was found to reduce  $N_2O$  emissions by 27 and 54% in a dry bean (*Phaseolus vulgaris* L.)-corn rotation and 19 and 51% in a barley-corn rotation, respectively, compared with surface-applied granular urea (Halvorson et al., 2010). In additional studies by Halvorson et al. (2011) and Halvorson and Del Grosso (2012), similar reductions in  $N_2O$  emissions were obtained under irrigated corn production with SuperU (46 and 53%) or AgrotainPlus (Koch Agronomic Services, with the same inhibitors as in SuperU) and urea-ammonium nitrate (62 and 70%). According to a meta-analysis of field data (113 datasets from 35 published studies through 2008), nitrification inhibitors were found to significantly reduce soil  $N_2O$  emissions from both chemical and organic fertilizers, whereas urease inhibitors were not effective (Akiyama et al., 2010).

Carbon dioxide and  $CH_4$  are also two important GHGs, with  $CH_4$  having a global warming potential 25 times that of  $CO_2$  (Solomon et al., 2007). Soil  $CO_2$  emissions are a result of organic C mineralization and plant root respiration, with roots contributing about one half of the  $CO_2$  emitted (Hanson et al., 2000). Agricultural soils can be a source and sink for atmospheric  $CO_2$ , depending on current and past land uses and agricultural management (Denef et al., 2011). In the case of  $CH_4$ , aerobic soils are generally a sink because of microbial oxidation, except in the case of rice (*Oryza sativa* L.) cultivation, where it contributes to 1.7% of total US anthropogenic  $CH_4$  emissions. Although  $N_2O$  emissions from soil management represent the largest fraction (i.e., 57%) of GHGs from agricultural activities (USEPA, 2016), there is interest in understanding the influence of N fertilizers and manure on soil  $CO_2$  and  $CH_4$  emissions. Some studies have investigated the effect of N inputs on  $CO_2$  and  $CH_4$  emissions under various climatic conditions (Sainju et al., 2008; Sistani et al., 2011; Plaza-Bonilla et al., 2014); however, limited emissions data are available for semiarid climates.

Alluvione et al. (2009) reported that N fertilization had no effect on cumulative  $CO_2$  emissions (2-yr average) from irrigated semiarid soils under continuous corn. In the same study, cumulative  $CH_4$  emissions were also not affected by N fertilization but were found to be 94% greater under no-till versus conven-

tional tillage, which is in contrast to other reports (Kessavalou et al., 1998; Ball et al., 1999; Plaza-Bonilla et al., 2014). In general, the capacity of soils to oxidize  $CH_4$  is reduced by cultivation compared with native soil ecosystems (Hütsch, 2001). Bronson and Mosier (1993) reported that the  $CH_4$  oxidation capacity of tilled and irrigated soils [under corn and wheat (*Triticum aestivum* L.) production] was 90% lower than that of native grassland soils. Haile-Mariam et al. (2008) found that  $CH_4$  flux in semiarid soils under sweet corn and potato (*Solanum tuberosum* L.) production in Washington State was, on average,  $-1.7$  and  $-2.3$  g  $CH_4$ -C ha $^{-1}$  d $^{-1}$ , respectively.

The objectives of this research were to: (i) determine the influence of N source (i.e., granular urea, SuperU, dairy manure, and composted dairy manure) and timing of manure application on  $N_2O$ ,  $CO_2$ , and  $CH_4$  emissions from a conventionally tilled and irrigated corn silage-barley-alfalfa rotation; (ii) estimate cumulative GHG losses during the growing season and noncrop periods; and (iii) determine  $N_2O$ -N losses per total amount of N applied. Dairy manure and composted dairy manure were selected as a N source in this field study, in addition to the urea fertilizers, since they are commonly used in south-central Idaho, where there are a large number of dairy operations. The impetus for this project was driven by the fact that no studies to date have investigated the influence of N source on GHG emissions from irrigated semiarid soils of south-central Idaho.

## MATERIALS AND METHODS

### Field Site and Treatments

The field site was located at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID, at 42°31'28" N, 114°22'17.50" W. This region has a semiarid climate and consists of cool wet winters and hot dry summers with a mean annual temperature of 8.7°C and precipitation of 284 mm. Soil at the site is a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) with the following average properties in the  $A_p$  horizon prior to initiation of the study: clay, 86 g kg $^{-1}$ ; silt, 708 g kg $^{-1}$ ; sand, 207 g kg $^{-1}$ ; pH, 7.8; electrical conductivity, 477  $\mu$ S m $^{-1}$ ;  $NO_3$ -N, 10.8 mg kg $^{-1}$ ;  $NH_4$ -N, 1.8 mg kg $^{-1}$ ; organic carbon, 7.2 g kg $^{-1}$ ; and bulk density, 1.3 g cm $^{-3}$ . From 2000 to 2012, the field was cropped with sugar beet (*Beta vulgaris* L.), corn, potato, barley, or dry bean and had not received manure applications during this time period. The last crop that was planted in 2012, before initiation of this study, was barley.

The experimental design was a randomized complete block with four replications, with a plot size of 21.3 by 22.9 m and a 15-m border strip between blocks. The fertilizer treatments were: (i) no fertilizer (control), (ii) granular urea, (iii) SuperU; (iv) composted dairy manure applied in the fall and granular urea applied in the spring (compost + urea); (v) dairy manure applied in the fall (fall manure); and (vi) dairy manure applied in the spring (spring manure). The fertilizers (urea and SuperU) were applied at agronomic rates based on spring soil N test data, whereas manure and compost were added at rates typical of this region.

Table 1 summarizes the quantity of N and C applied for each treatment and the timing of the applications. The average annual compost and manure application rates were 28 and 112 Mg ha<sup>-1</sup> (wet wt. basis), respectively. Prior to silage corn planting in spring 2013, P (as monoammonium phosphate) was applied to the urea and SuperU treatments at a rate of 34 kg P ha<sup>-1</sup>, based on soil test data and University of Idaho recommendations (Brown et al., 2010). The N applied in the monoammonium phosphate was accounted for in the total N applied in the urea and SuperU treatments (Table 1). After broadcasting, the treatments were incorporated into the soil using a tandem disk within 24 h. The control plots were also disked. No treatments were applied to alfalfa in 2015 because there was sufficient soil inorganic N for alfalfa establishment, with the subsequent year's N requirements being met by plant-rhizobia symbiotic N fixation. Selected physical and chemical properties of the dairy manure and compost are presented in Table 2. The moisture content of the manure ranged from 48 to 61%, whereas the respective values for compost were 7 and 15% in 2012 and 2013. The C/N ratios ranged from a low of 9.9 for compost to 14.8 for manure.

Silage corn ('P925HR HX1', Pioneer), barley ('Moravian 69', MillerCoors), and alfalfa ('Grandstand', Dyna-Gro) were planted on 16 May 2013 [day of the year (DOY): 136], 9 Apr. 2014 (DOY: 99), and 16 Apr. 2015 (DOY: 106), respectively. The respective seeding rates were 32, 124, and 34 kg seed ha<sup>-1</sup> (approximately equal to 8.6 × 10<sup>4</sup>, 4.1 × 10<sup>6</sup>, and 1.5 × 10<sup>7</sup> seeds ha<sup>-1</sup>). Herbicide applications at label rates for corn occurred on 5 [generic glyphosate (*N*-[phosphonomethyl] glycine)] and 26 [glyphosate and Status (BASF Corporation, Research Triangle Park, NC)] June 2013 (DOY: 156 and 177), those for barley [Colt + Sword (Loveland Products, Inc., Loveland, CO) and Affinity BroadSpec (Dupont Crop Protection, Wilmington, DE)] on 28 May 2014 (DOY: 148), and that for alfalfa (Raptor, BASF Corporation) on 18 June 2015 (DOY: 169). The active ingredients in Status are sodium salt of diflufenzopyr [2-(1-[[[3,5-difluorophenylamino] carbonyl]-hydrazono]ethyl)-3-pyridinecarboxylic acid] and dicamba (3,6-dichloro-2-methoxybenzoic acid), those for Colt + Sword are fluroxypyr 1-methylheptyl ester (4-amino-3,5-dichloro-6-fluoro-2-pyridyloxyacetic acid, 1-methylheptyl ester) and methyl phenoxy ester (2-methyl-4-chlorophenoxyacetic acid, 2-ethylhexyl ester), those for BroadSpec are thifensulfuron-methyl [Methyl 3-[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino]carbonyl]amino]sulfonyl]-2-thiophenecarboxylate] and tribenuron-methyl [methyl 2-[[[*N*-(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methyl-

**Table 1. Average amount of N and C added to the plots.**

	Control	Urea	SuperU	Compost + urea†	Fall manure	Spring manure
	kg N ha <sup>-1</sup>					
9 Oct. 2012 (DOY: 283)§	–	–	–	228	1,065	–
13 May 2013 (DOY: 133)	0	186‡	186‡	168	–	570
4 Nov. 2013 (DOY: 308)	–	–	–	350	1,194	–
7 Apr. 2014 (DOY: 97)	0	67	67	67	–	937
	kg C ha <sup>-1</sup>					
9 Oct. 2012 (DOY: 283)	–	–	–	2989	16,001	–
13 May 2013 (DOY: 133)	–	–	–	–	–	7,945
4 Nov. 2013 (DOY: 308)	–	–	–	3384	15,479	–
7 Apr. 2014 (DOY: 97)	–	–	–	–	–	13,244

† Compost and urea were applied in the fall and spring, respectively.

‡ Includes N supplied with monoammonium phosphate.

§ DOY, day of the year.

**Table 2. Selected physical and chemical properties of the dairy manure and compost.**

Year	Season	Treatment	Moisture	C	N	C/N
			%	g kg <sup>-1</sup>		
2012	Fall	Manure	53	281	19	14.8
	Fall	Compost	7	144	11	13.1
2013	Spring	Manure	48	181	13	13.9
	Fall	Manure	56	291	22	13.2
	Fall	Compost	15	119	12	9.9
2014	Spring	Manure	61	275	19	14.5

amino]carbonyl) amino]sulfonyl]benzoate], and that for Raptor is ammonium salt of imazamox [2-(4,5-dihydro-4-methyl-4-[1-methylethyl]-5-oxo-1*H*-imidazol-2-yl)-5-(methoxymethyl)-3-pyridinecarboxylic acid].

Crop harvest dates were 12 Sept. 2013 (DOY: 255) for silage corn, 20 Aug. 2014 (DOY: 232) for barley, and 15 July and 8 Sept. 2015 (DOY: 199 and 251) for alfalfa. Silage corn was removed from the field the same day it was chopped, barley straw was baled and removed after grain harvest, and alfalfa was baled about 1 wk after it was windrowed. Plant subsamples were collected and weighed, then dried in a constant-temperature forced-draft oven for 48 h at 60°C and reweighed to determine the dry matter fraction. Yields on a dry matter basis were determined by multiplying the weight of harvested material by the dry matter fraction (Table 3).

An onsite weather station (Campbell Scientific, Inc., Logan, UT) was placed at the northwest corner of the field in a control plot with soil temperature measured at 6 cm. Soil volumetric water content (VWC) at 0 to 15 cm was measured at the time

**Table 3. Crop yield data from the monitoring periods.**

Treatment	Silage corn (2013)	Barley grain (2014)	Alfalfa (2015)
	kg ha <sup>-1</sup> (dry wt.)		
Control	19,748a†	4187a	7044b
Urea	20,076a	4628a	8280ab
SuperU	20,772a	4678a	8084ab
Compost + urea	20,772a	4019a	8298ab
Fall manure	21,828a	4437a	8512ab
Spring manure	22,098a	5003a	9052a

† Mean values within a column followed by the same lowercase letter are not significantly different at the 0.05 probability level.

of gas sampling by manually placing a CS630-L Time Domain Reflectometry probe (Campbell Scientific, Inc., Logan, UT) into the soil just outside the gas flux measurement area. Precipitation data were obtained from the Twin Falls (Kimberly) Idaho AgriMet weather station, which is 3.8 km northeast of the field site (<http://www.usbr.gov/pn/agrimet/agrimetmap/twfida.html>, accessed 30 Mar. 2017). Irrigation water (Snake River water from a canal system) was applied using a lateral-move irrigation system. Approximately 20 mm were applied two or three times per week to meet crop water needs based on the AgriMet data.

## Gas Flux Measurements

Nitrous oxide, CO<sub>2</sub>, and CH<sub>4</sub> flux measurements were conducted using a vented, non-steady-state, closed chamber technique. The gas chambers were built according to USDA-ARS GRACEnet sampling protocols (Parkin and Venterea, 2010). In brief, a rectangular chamber (78.5 by 40.5 by 10 cm) was manufactured from an aluminum sheet 3.2 mm thick and fitted with a sampling port and vent on the top. To insulate the chamber, a layer of corkboard was applied to the surface, which was then coated with a layer of Mylar tape. In the field, each chamber was placed onto an aluminum anchor that was set 10 cm into the soil and sealed using a water channel. Duplicate anchors were placed about 1 m apart in each plot and were set parallel to the crop row to cover the row and inter-row space (76.2 cm for corn, 17.8 cm for barley, and 19.1 cm for alfalfa row spacing). In the case of corn, the anchor was centered over one row and covered only one half of each adjacent inter-row space. The anchors were temporarily removed during soil tillage, fertilizer application, and harvest but otherwise remained in the plots at all times. Corn, barley, and alfalfa within the anchor area were cut so that they did not extend above the water channel.

An air sample from within the chamber was collected at 0, 15, and 30 min using a 30-mL polypropylene syringe with a stopcock. Afterward, the syringes were stored in a cooler (without ice) until transported to the laboratory. Twenty-five-mL air samples were then injected into evacuated 12-mL Exetainer vials

with gray butyl rubber septa (Labco Limited, Lampeter, UK), which were then analyzed via gas chromatography. The gas chromatograph (model 7890A, Agilent Technologies, Santa Clara, CA) was equipped with a GC 120 autosampler and electron capture, thermal conductivity, and flame ionization detectors to quantify N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub>, respectively. Gas fluxes were determined from a linear or nonlinear increase in the concentration within the chamber headspace over time (Hutchinson and Mosier, 1981). Estimates of daily gas emissions between sampling days were generated using the adjacent sampling dates and the FORECAST function in Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA).

Gas samples were collected during the following periods each year: 2013: 20 May to 30 Oct. (DOY: 140–303); 2014: 5 Mar. to 10 Dec. (DOY: 64–344); and 2015: 8 Jan. to 10 Nov. (DOY: 8–314). Gas samples were collected two to three times weekly during the spring, summer, and fall and on an irregular basis during the winter when temperatures were above freezing.

## Statistical Analysis

Estimated cumulative N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions; average fluxes; and crop yield data were statistically analyzed using a factorial ANOVA in SAS (SAS Institute Inc., Cary, NC). All ANOVA data were checked for normality and were log-transformed when necessary. Mean comparisons were performed using the Ryan–Einot–Gabriel–Welsch multiple range test at an  $\alpha$  level of 0.05. Statements of statistical significance were based on  $P < 0.05$ .

## RESULTS AND DISCUSSION

### Environmental Conditions

During the GHG monitoring periods in 2013, 2014, and 2015, the respective total precipitation accumulations were 50, 275, and 196 mm, with irrigation totals of 605, 418, and 616 mm (Fig. 1). The irrigation events occurred during the following time periods: 20 May to 28 Aug. 2013 (DOY: 140–240), 12 May to 21 July 2014 (DOY: 132–202), and 4 May to 6 Oct. 2015 (DOY: 124–279). The data presented in Fig. 2, Fig. 3, and Fig. 4 show that the 0 to 15 cm soil VWC generally fluctuated between 0.1 and 0.4 m<sup>3</sup> m<sup>-3</sup>, but with an increasing trend during the growing season. Overall, the VWCs for the treatments tracked each other very closely. As expected, soil temperature at 6 cm below the surface was lowest in winter, early spring, and late fall, but was greater on average from May to September. During the growing season (i.e., seeding to plant harvest), the average soil temperatures under corn, barley, and alfalfa were 20, 16, and 18°C, respectively (data not shown). The respective highest average daily soil temperatures under corn, barley, and alfalfa were 29°C (DOY: 182), 21°C (DOY: 212), and 23°C (DOY: 160 and 181). Because the soil temperature probe was installed in a control plot only, we do not know if temperature was influenced by the treatments.

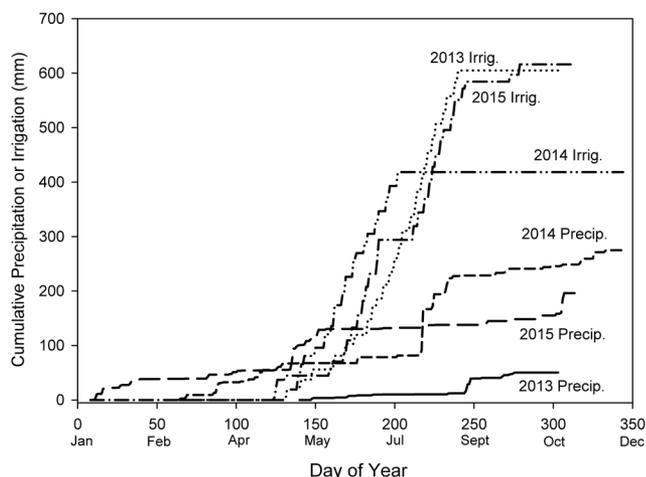


Fig. 1. Cumulative precipitation and irrigation amounts during the monitoring periods in 2013, 2014, and 2015.

## Crop Yields

Silage corn and barley grain yields were statistically similar among the N treatments ( $P > 0.34$ ; Table 3). Additionally, biomass yields in the controls (i.e., no N) were similar to the N-treated plots for corn ( $P > 0.65$ ) and barley ( $P > 0.69$ ), indicating that the control soils produced sufficient plant-available N during the monitoring periods. The high N mineralization potential of the aridisols in south-central Idaho is a commonly observed trait (Stanford et al., 1977; Westermann and Crothers, 1980). Alfalfa yields, based on two cuttings, were similar among the N treatments and controls ( $P > 0.21$ ), except in the case of spring manure versus the control ( $P < 0.04$ ). Once again for clarification, no N was applied in the fall and spring before the alfalfa was planted in 2015.

## Nitrous Oxide Fluxes

Greenhouse gas measurements commenced prior to N applications and irrigation to determine baseline emissions and en-

sure that maximum  $N_2O$  fluxes were captured. Under silage corn (2013), the maximum measured  $N_2O$ -N flux from SuperU and spring manure occurred on Days 140 ( $15 \text{ g ha}^{-1} \text{ d}^{-1}$ ) and 142 ( $22 \text{ g ha}^{-1} \text{ d}^{-1}$ ), respectively, then from urea and compost + urea on Day 156 ( $31 \text{ g ha}^{-1} \text{ d}^{-1}$ ), followed by a decline to background levels (Fig. 2). During the same period,  $N_2O$  emissions from fall manure were also elevated, although these fluxes were lower than those from compost + urea and spring manure. Starting on Day 182,  $N_2O$  emissions increased again slightly from fall and spring manure, reaching maximum flux on Day 190. This short-term increase corresponds with the highest average daily soil temperature of  $29^\circ\text{C}$  during the monitoring period.

In 2014,  $N_2O$  fluxes were about 45-fold greater on average from fall manure versus the other treatments in the beginning of the monitoring period (DOY: 64–84) before the N inputs occurred and barley was planted (Fig. 3). This is because the labile N that was not used by the soil microorganisms over the fall and winter was actively metabolized when the soils began to warm in early March. Within a few days of spring fertilizer and manure

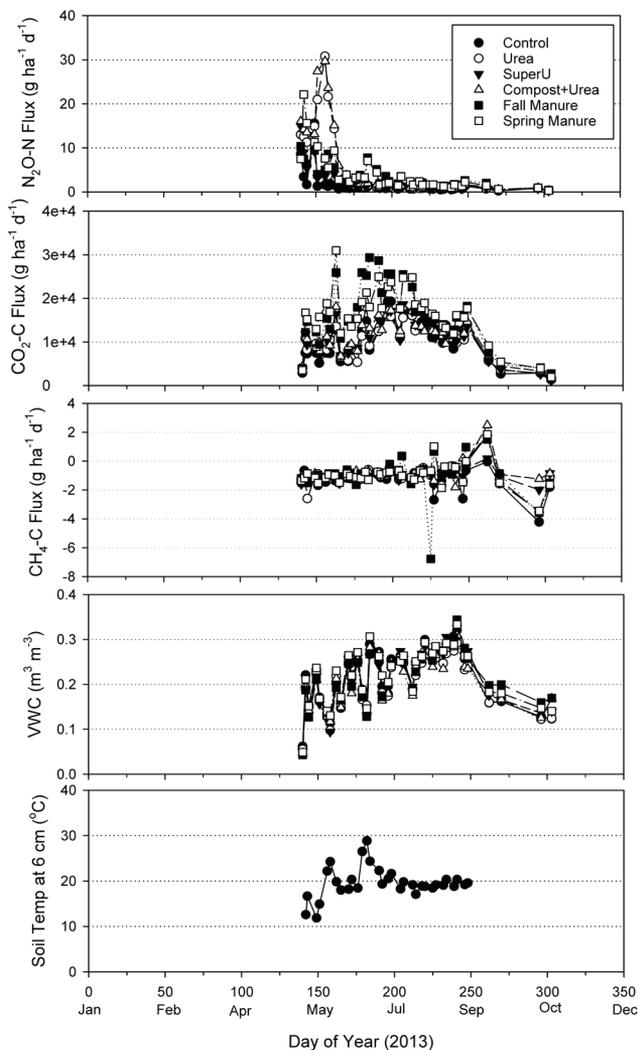


Fig. 2. Average  $N_2O$ ,  $CO_2$ , and  $CH_4$  fluxes for the control, urea, SuperU, compost + urea, fall manure, and spring manure treatments and volumetric water content (VWC) and soil temperature during the monitoring period in 2013 with silage corn as the crop. Soil temperature after Day 248 was not available because of a probe malfunction.

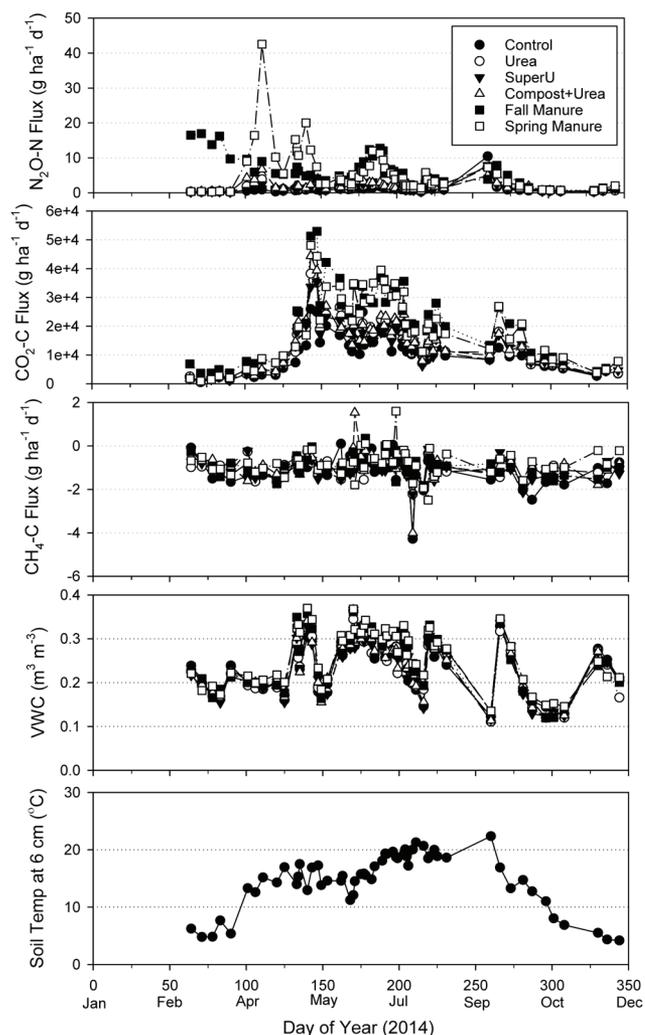


Fig. 3. Average  $N_2O$ ,  $CO_2$ , and  $CH_4$  fluxes for the control, urea, SuperU, compost + urea, fall manure, and spring manure treatments and volumetric water content (VWC) and soil temperature during the monitoring period in 2014 with barley as the crop.

application on Day 97, the  $N_2O$ -N emissions began to increase from all treatments; however, the magnitude was greatest from spring manure on Day 111 ( $43 \text{ g ha}^{-1} \text{ d}^{-1}$ ). When irrigation water was applied for the first time on Day 132, the emissions began to increase slightly, with another large  $N_2O$ -N flux occurring from spring manure on Day 140 ( $20 \text{ g ha}^{-1} \text{ d}^{-1}$ ). Thereafter,  $N_2O$  emissions from the fall and spring manure peaked on Day 180, then generally tracked the other treatments at near background rates.

During alfalfa production in 2015, peak  $N_2O$  fluxes occurred on Days 128 and 216 (Fig. 4). The first peak coincided with the initial irrigation event that occurred on Day 124, whereas the second maximum peak occurred about 2 wk after the first harvest on Day 216 (two irrigation events, totaling 5 cm of water, occurred on Days 212 and 215). The emissions from Day 124 to the final harvest of the season on Day 251 were generally the greatest from fall and spring manure. Because the N treatments

were not applied in 2015 (Table 1), this indicates that there was a residual effect of the manures.

Figure 5 presents box-and-whisker plots of GHG flux data from each monitoring period by year. The N treatments with the largest  $N_2O$  emission fluctuations in 2013 were urea and compost + urea, with the control and compost + urea having the lowest and highest average fluxes ( $P = 0.02$ ), respectively. During the monitoring period in 2014, the average  $N_2O$  fluxes from fall and spring manure were statistically similar and greater than those from the other N treatments ( $P < 0.0001$ ). The same result was obtained in 2015 but the average fluxes for fall and spring manure were slightly lower.

## Carbon Dioxide Fluxes

Carbon dioxide fluxes from the fall and spring manure tracked the control and other N treatments and tended to be slightly higher only during the monitoring periods in 2013 and 2014 (Fig. 2 to Fig. 4). Under silage corn, the maximum  $CO_2$ -C fluxes from fall ( $29 \text{ kg ha}^{-1} \text{ d}^{-1}$ ) and spring manure ( $31 \text{ kg ha}^{-1} \text{ d}^{-1}$ ) occurred on Days 184 and 162, respectively, with the greatest emissions occurring from these treatments until Day 212 (Fig. 2). From Day 214 forward,  $CO_2$ -C emissions were of similar magnitude among the treatments and gradually declined to substantially lower levels by Day 303. Under barley, maximum  $CO_2$ -C flux from fall ( $52 \text{ kg ha}^{-1} \text{ d}^{-1}$ ) and spring ( $48 \text{ kg ha}^{-1} \text{ d}^{-1}$ ) manure occurred on Days 147 and 143 (about 1.7-fold greater than under corn) and then emissions declined by Day 287 (Fig. 3). The highest  $CO_2$ -C fluxes under alfalfa occurred during Days 168 to 194, with a maximum of about  $50 \text{ kg ha}^{-1} \text{ d}^{-1}$  (Fig. 4). On average,  $CO_2$  fluxes were statistically greater from fall and spring manure in 2013 and 2014 ( $P < 0.0001$ ), but not in 2015 ( $P > 0.98$ ) (Fig. 5). Although the C/N ratios of the manure and compost were similar (Table 2), the increased  $CO_2$  emissions from the fall and spring manure are not surprising, as the amount of C added to those plots was several times more than the compost + urea plots (Table 1).

## Methane Fluxes

Methane emissions were negligible during all 3 yr, with most of the recorded fluxes being negative, which is presumably a result of oxidation by methanotrophic microbes (Goulding et al., 1995). During 2013, the fluxes were generally between  $-1.5$  and  $0 \text{ g CH}_4\text{-C ha}^{-1} \text{ d}^{-1}$ , with some larger negative fluxes occurring several times during the monitoring period (Fig. 2). Some positive  $CH_4$  fluxes were recorded on Days 206, 227, 246, and 262, suggesting increased activity of methanogenic bacteria or reduced  $CH_4$  oxidation. The positive fluxes occurred in conjunction with moisture events; however, with 26 irrigation events (data not shown), more positive fluxes should have theoretically occurred during the monitoring period. Although we did not directly measure the potential of the soil to produce and oxidize  $CH_4$ , the uptake of atmospheric  $CH_4$  obviously occurred at a higher rate than  $CH_4$  production. During 2014, uptake of atmospheric  $CH_4$  occurred on the majority of the measurement

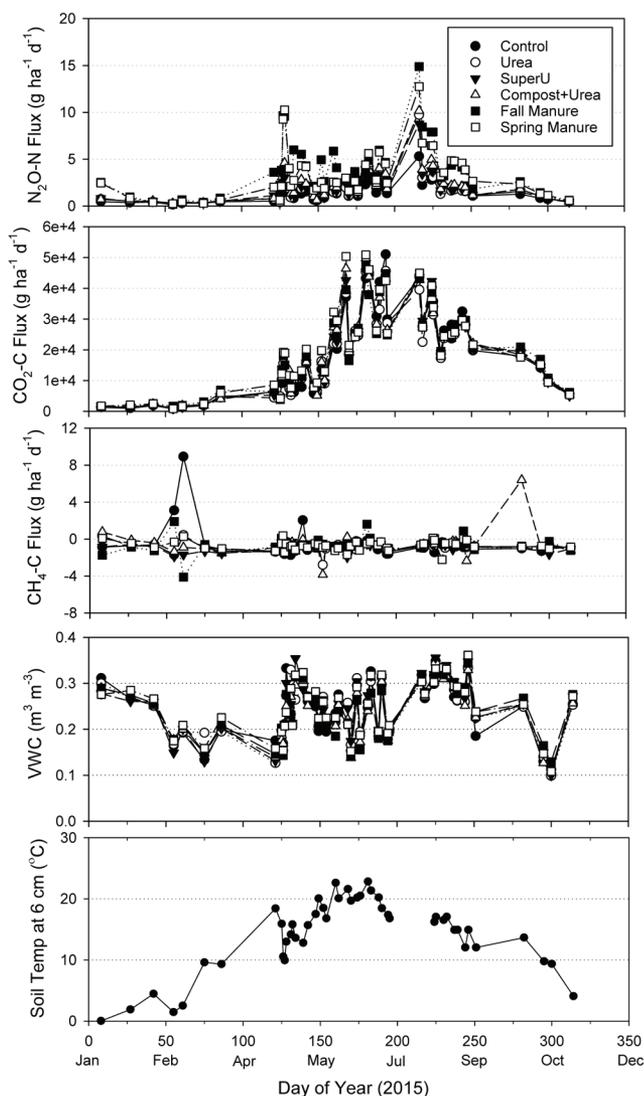


Fig. 4. Average  $N_2O$ ,  $CO_2$ , and  $CH_4$  fluxes for the control, urea, SuperU, compost + urea, fall manure, and spring manure treatments and volumetric water content (VWC) and soil temperature during the monitoring period in 2015 with alfalfa as the crop.

days (Fig. 3). Positive  $\text{CH}_4$  fluxes occurred on only a few days, although there did not appear to be any discernable trend with respect to N treatment. Similar  $\text{CH}_4$  flux patterns occurred during the 2015 monitoring period with alfalfa, except that the highest positive fluxes (control, Day 60; compost + urea, Day 282) were several times greater than what was observed in 2013 and 2014. Overall, there was little difference among the average  $\text{CH}_4$  fluxes over the monitoring periods, except in 2014, where the spring manure was statistically greater than the control (Fig. 5).

### Cumulative GHG Emissions

Estimated cumulative  $\text{N}_2\text{O}$ -N,  $\text{CO}_2$ -C, and  $\text{CH}_4$ -C emissions during the monitoring periods in 2013, 2014, and 2015 are presented in Table 4. In 2013,  $\text{N}_2\text{O}$  emissions were reduced by 53% with use of SuperU compared with urea application. In contrast,  $\text{N}_2\text{O}$  emissions were not lowered with SuperU in 2014, nor was there any residual effect of the inhibitors in 2015. There was also no significant difference in cumulative  $\text{N}_2\text{O}$ -N emissions between fall- and spring-applied manure during the three moni-

toring periods, which produced the greatest emissions in 2014 and 2015. The increased  $\text{N}_2\text{O}$  emissions from the manure plots during those years but not in 2013 suggests that there was a cumulative effect of manure application or that crop N use differed, allowing more mineral N to be nitrified or denitrified. Estimated cumulative  $\text{CO}_2$  emissions were greatest from both fall and spring manure in 2013 and 2014, whereas the  $\text{CO}_2$  emissions were statistically similar among all treatments in 2015. With respect to cumulative  $\text{CH}_4$  emissions, all values were negative and no statistical differences were found among the treatments during any year.

### Nitrous Oxide Loss as a Function of Applied N

The  $\text{N}_2\text{O}$ -N emission losses as a percentage of total N applied are presented in Fig. 6. In 2013, the  $\text{N}_2\text{O}$ -N loss for urea (0.21%) was greater than that for the other N treatments, with fall manure having the lowest proportional loss of applied N (0.02%). In 2014, there was no statistical difference in  $\text{N}_2\text{O}$ -N losses among the N treatments. Although the  $\text{N}_2\text{O}$ -N emission losses as a per-

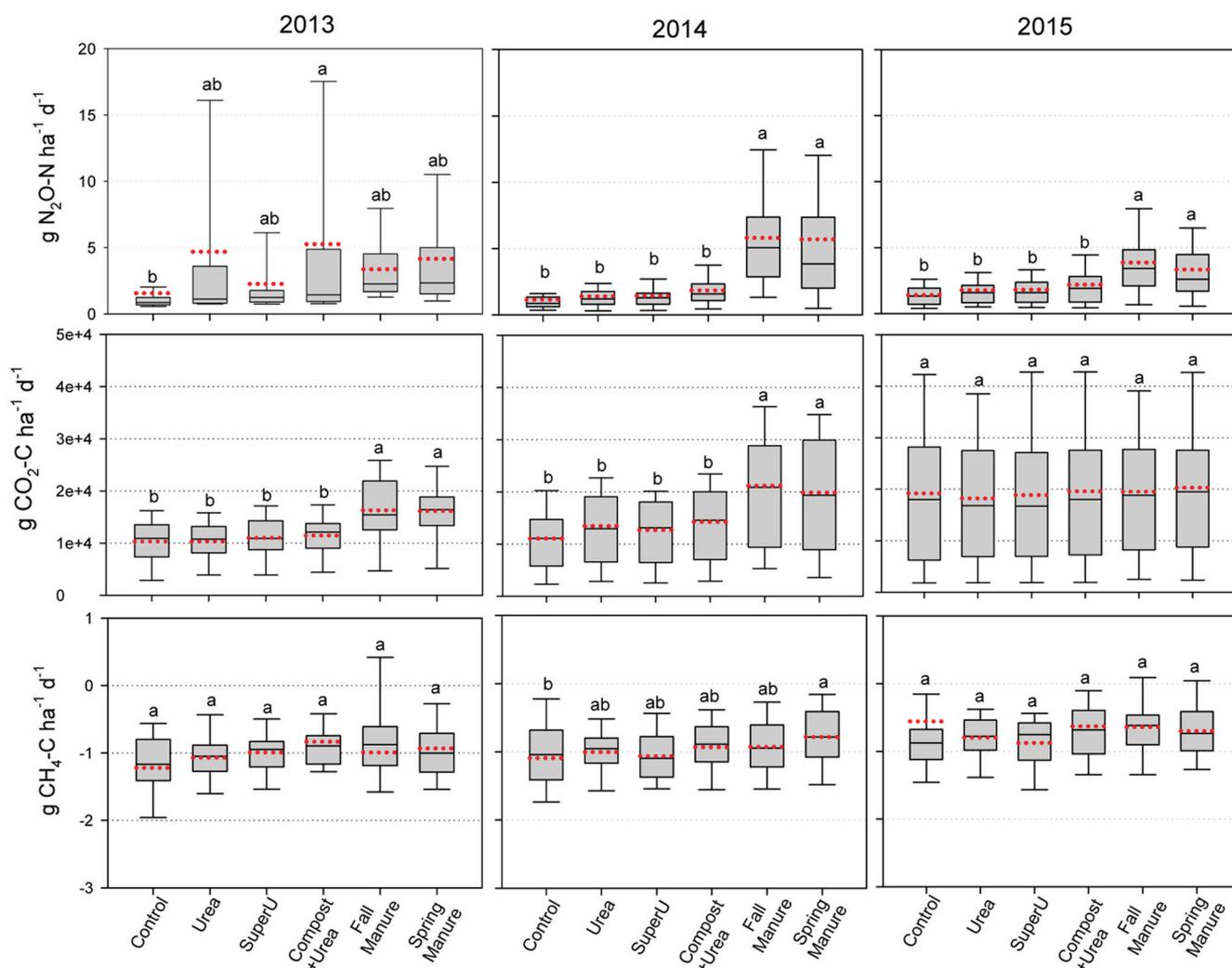


Fig. 5. Box-and-whisker plots of daily  $\text{N}_2\text{O}$ ,  $\text{CO}_2$ , and  $\text{CH}_4$  fluxes for the control, urea, SuperU, compost + urea, fall manure, and spring manure treatments during the monitoring periods in 2013, 2014, and 2015. The horizontal lines, from top to bottom including the whisker caps, represent the 90th, 75th, 50th, 25th, and 10th percentiles; the red dotted line represents the average flux. Lowercase letters above the boxes indicate significant differences between the treatments at a 0.05 probability level.

**Table 4. Estimated cumulative N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions during the monitoring periods.**

Treatment	2013†	2014‡	2015§
	kg N <sub>2</sub> O-N ha <sup>-1</sup>		
Control	0.21c¶	0.40b	0.36c
Urea	0.59a	0.44b	0.47bc
SuperU	0.28bc	0.43b	0.48bc
Compost + urea	0.66a	0.52b	0.55abc
Fall manure	0.46abc	1.5a	0.94a
Spring manure	0.54ab	1.5a	0.81ab
	kg CO <sub>2</sub> -C ha <sup>-1</sup>		
Control	1472b	2437c	4620a
Urea	1474b	2996bc	4453a
SuperU	1553b	2839bc	4587a
Compost + urea	1654b	3147b	4673a
Fall manure	2307a	4679a	4809a
Spring manure	2305a	4308a	4904a
	kg CH <sub>4</sub> -C ha <sup>-1</sup>		
Control	-0.20a	-0.33a	-0.18a
Urea	-0.18a	-0.29a	-0.26a
SuperU	-0.17a	-0.31a	-0.31a
Compost + urea	-0.17a	-0.28a	-0.19a
Fall manure	-0.17a	-0.27a	-0.31a
Spring manure	-0.17a	-0.23a	-0.25a

† 20 May to 30 October; 164 d of measurement.

‡ 5 March to 11 December; 281 d of measurement.

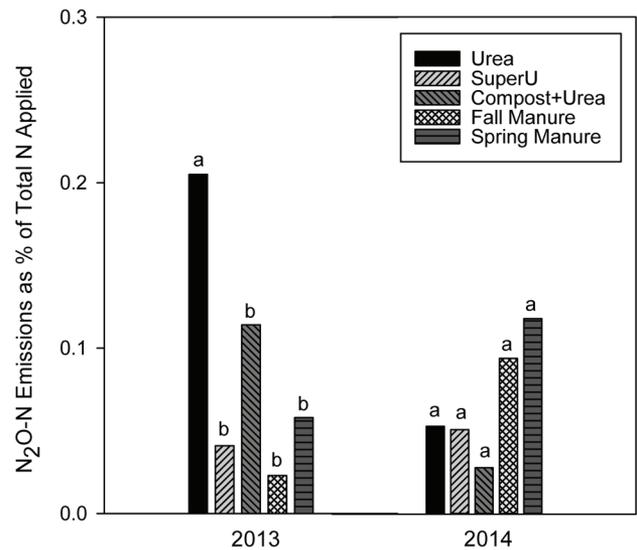
§ 8 January to 10 November; 307 d of measurement.

¶ Values within a column followed by the same lowercase letter are not significantly different at the 0.05 probability level.

centage of applied N are low overall, the benefits of using SuperU are quite substantial. The 2013 results indicate that the fertilizer-induced component of N<sub>2</sub>O emissions could be reduced by up to 80% in semiarid irrigated cropping systems through use of SuperU. The fact that N<sub>2</sub>O emission reductions with SuperU occurred only during corn production suggest that there might be a crop-, weather-, or management-dependent effect.

## CONCLUSIONS

Novel management practices are needed to reduce GHG emissions, especially N<sub>2</sub>O, from irrigated cropping systems without impacting crop quality and yields. The results from this study suggest that application of a stabilized urea source, such as SuperU, could be useful to help achieve that objective. During corn production, cumulative N<sub>2</sub>O-N emissions were 53% lower with SuperU than with granular urea, and crop yields were unaffected. However, SuperU did not mitigate N<sub>2</sub>O emissions under barley production, thus additional testing is necessary to verify the consistency of this product under these crops. Overall, N<sub>2</sub>O-N emission losses as a percentage of total N applied were ≤0.21%, which is lower than the Tier 1 emissions factor of 1% used by the IPCC. It was also discovered that N<sub>2</sub>O fluxes, on average, and estimated cumulative emissions were similar between fall- and spring- applied manure, although a definitive statement on the timing of manure application on emissions cannot be made since limited wintertime gas samples were collected. Carbon dioxide emissions were similar from fall and spring ma-



**Fig. 6. Nitrous oxide emission losses as a percentage of total N applied for urea, SuperU, compost + urea, fall manure, and spring manure in 2013 and 2014. Values were calculated by subtracting the cumulative N<sub>2</sub>O-N emissions of the control from the N treatments (Table 4), then dividing by the appropriate N rate in Table 1. Lowercase letters above the vertical bars indicate significant differences between the treatments at a 0.05 probability level.**

nure and were greater than the other N treatments during the first 2 yr. In addition, there was no legacy effect of manure on CO<sub>2</sub> emissions under alfalfa production, which is in contrast to what occurred with N<sub>2</sub>O emissions. Methane emissions were similar among the treatments during all years and negative values indicate that oxidation of atmospheric CH<sub>4</sub> was greater than CH<sub>4</sub> production in soil. The data generated from this study will be useful for improving GHG emissions inventories for irrigated cropping systems in semiarid regions and validating the associated IPCC emissions factors.

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