

# Urea Decreases Nitrous Oxide Emissions Compared with Anhydrous Ammonia in a Minnesota Corn Cropping System

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Quantifying  $N_2O$  emissions from corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] fields under different fertilizer regimes is essential to developing national inventories of greenhouse gas emissions. The objective of this study was to compare  $N_2O$  emissions in plots managed for more than 15 yr under continuous corn (C/C) vs. a corn-soybean (C/S) rotation that were fertilized during the corn phase with either anhydrous  $NH_3$  (AA) or urea (U). During three growing seasons,  $N_2O$  emissions from corn following corn were nearly identical to corn following soybean. In both systems, however,  $N_2O$  emissions with AA were twice the emissions with U. After accounting for  $N_2O$  emissions during the soybean phase, it was estimated that a shift from C/S to C/C would result in an increase in annual emissions of  $0.78 \text{ kg N ha}^{-1}$  (equivalent to  $0.11 \text{ Mg CO}_2\text{-C ha}^{-1}$ ) when AA was used, compared with only  $0.21 \text{ kg N ha}^{-1}$  ( $0.03 \text{ Mg CO}_2\text{-C ha}^{-1}$ ) with U. In light of trends toward increased use of U, these results suggest that fertilizer-induced soil  $N_2O$  emissions may decline in the future, at least per unit of applied N, although further study is needed in different soils and cropping systems. While soil  $CO_2$  emissions were 20% higher under C/C, crop residue from the prior year did not affect soil inorganic N or dissolved organic C during the subsequent season. We also compared different flux-calculation schemes, including a new method for correcting chamber-induced errors, and found that selection of a calculation method altered  $N_2O$  emissions estimates by as much as 35%.

**Abbreviations:** AA, anhydrous ammonia; C/C, continuous corn; Cc, corn after corn; C/S, corn-soybean; Cs, corn after soybean; DOC, dissolved organic carbon; GHG, greenhouse gas; Sc, soybean after corn; U, urea; UAN, urea-ammonium nitrate; WFPS, water-filled pore space.

Corn and soybean production together account for nearly half of all land used for crops in the United States and comprise approximately 8% of total area of the contiguous United States (National Agricultural Statistics Service, 2009). Therefore, quantifying soil emissions of  $N_2O$  associated with production of these crops is essential to developing accurate greenhouse gas (GHG) inventories for agriculture. Also, due to the high global warming potential of  $N_2O$  compared with  $CO_2$  ( $\sim 300:1$ ),  $N_2O$  emissions are critical in determining the effectiveness of corn-based biofuel as an alternative to fossil fuels for reducing GHG emissions (Forster et al., 2007; Crutzen et al., 2008). In determining the total GHG impact of corn production, the analysis must consider changes in the emissions of  $N_2O$  (and other GHGs) resulting from any shifts from other land uses into corn production.

Because C/S rotations have been a dominant cropping system throughout much of the central United States during the past several decades, it is important to quantify the differences in  $N_2O$  emissions resulting from a C/C cropping system compared with a C/S rotation. Wide fluctuations in both corn and soybean prices and other pressures have resulted in dramatic shifts in the amount of land devoted

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to either crop. In 2007, the amount of land devoted to corn increased by 22% while soybean land decreased by 14% compared with 2006 (National Agricultural Statistics Service, 2009). The trend was partly reversed in 2008, with a 9% decrease and 16% increase in land devoted to corn and soybean, respectively. The longer term trend shows increasing land devoted to corn (up 9% since 2003) and more stability for soybean (up 3% since 2003).

There have been few published studies comparing  $N_2O$  emissions under C/C and C/S, particularly for systems that have been in long-term management. Higher  $N_2O$  emissions from C/C compared with the corn phase of a C/S rotation might be expected due to greater plant residue inputs from the previous growing season (i.e., from corn) (e.g., Wilson and Al-Kaisi, 2008). Higher amounts of residue could generate higher  $N_2O$  emissions if they result in higher dissolved organic C (DOC) levels to promote denitrification (Burford and Bremner, 1975). On the other hand, the lower C/N ratio of soybean residue ( $\sim 15$ ) compared with corn ( $> 50$ ) (Burgess et al., 2002; Toma and Hatano, 2007) might be expected to generate higher  $N_2O$  emissions from C/S by increasing the levels of soil  $NH_4^+$  and  $NO_3^-$  during the subsequent growing season. Existing field studies have shown conflicting results. Drury et al. (2008) found that  $N_2O$  emissions from C/C were higher than the corn phase of a C/S rotation, while Mosier et al. (2006) found the opposite result. Neither study reported soil inorganic N or DOC data.

Management of fertilizer N is one of the most critical factors affecting  $N_2O$  emissions (Mosier et al., 1998). Anhydrous  $NH_3$  and U are two of the most commonly used fertilizers in the United States and the world. There are few studies, however, comparing  $N_2O$  emissions following AA and U application within the same cropping system. The use of AA in the United States has declined by 15% during the past three decades, while U use has nearly tripled (Economic Research Service, 2009). There has also been a shift toward more U and less AA consumption worldwide (Glibert et al., 2006). Thus, if  $N_2O$  emissions following AA and U application differ substantially, these trends in fertilizer use may substantially alter  $N_2O$  emissions at national and global scales.

The primary objective of the current study was to compare  $N_2O$  emissions and soil chemical properties following application of either AA or U fertilizer in research plots in southeastern Minnesota that have been managed for more than 15 yr under C/C vs. a C/S rotation. We also applied a new flux-calculation technique (Venterea, 2010) that accounts for chamber-induced errors, and compared total  $N_2O$  emissions estimated using different calculation methods.

## MATERIALS AND METHODS

### Site Description and Experimental Design

The site is located at the University of Minnesota's Outreach, Research, and Education Park in Rosemount, MN ( $44^\circ 45' N$ ,  $93^\circ 4' W$ ). Soil at the site is a Waukegan silt loam (a fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll) with sand, silt, and clay contents of 220, 550, and 230  $g\ kg^{-1}$ , respectively, and organic C

of 26 to 30  $g\ C\ kg^{-1}$  in the upper 0.2 m. The loess-derived silt loam is underlain starting at 0.6 to 0.8 m by outwash sands. Annual 30-yr mean precipitation and temperature are 879 mm and  $6.4^\circ C$ , respectively (Minnesota Climatology Working Group, 2009). The site was planted in alfalfa before 1987 and in corn from 1987 to 1989. A plot study was established in 1990 using a randomized complete block design with three crop treatments in each of three blocks. The crop treatments consisted of corn after corn (Cc), corn after soybean (Cs), and soybean after corn (Sc). The Cs and Sc treatments were rotated between plots each year and together comprised a C/S rotation. Each plot measured 27.4 m wide by 61 m long with a row spacing of 0.76 m (36 rows per plot).

In spring 2005, nine plots (three each of the Cc, Cs, and Sc treatments) were subdivided into two subplots, each 9.1 m (12 rows) wide (the remaining 12 rows of each plot were not used in the study). Each spring, the two subplots in the Cc and Cs treatments received 146  $kg\ N\ ha^{-1}$  applied 1 to 2 wk before planting either as (i) AA, which was knife injected 0.15 to 0.20 m below the surface, or (ii) U, which was surface broadcast and then incorporated by disking to a depth of 0.15 m on the same day. The Sc treatments (i.e., the soybean phase of the rotation) did not receive fertilizer; however, 1 yr before initiating the study (i.e., in spring 2004), plots planted in corn that were to receive the Sc treatment in 2005 were subdivided into two subplot fertilizer treatments per above. Thus, starting in 2005 and thereafter, the AA and U subplot designations in the Sc treatment reflected the previous year's fertilizer management (i.e., during the corn phase of the rotation). The fertilizer subplot treatments were maintained in the same 12-row subsections of each main plot for 2005, 2006, and 2007. Fertilizer application equipment was calibrated initially using manufacturer-recommended settings, with further refinement based on trial runs in nearby fields to more accurately achieve the desired N application rates.

Corn and soybean were planted at seeding rates of 79,000 and 370,000  $ha^{-1}$ , respectively. Each year, corn was planted between 5 May and 17 May and soybean was planted between 24 May and 2 June. The corn cultivar had a maturity date of 98 d, while soybean had maturity indices ranging from 1.5 to 1.8. Crops were harvested after the plants were physiologically mature using a John Deere 4400 combine (Deere & Co., Moline, IL). For each subplot, the middle eight rows of corn were harvested using a four-row corn head, while all 12 rows of soybean were harvested using a six-row soybean head. After each plot area was harvested, the grain was transferred from the combine to a grain wagon (Unverferth Mfg., Kalida, OH) equipped with tared, calibrated load cells for obtaining the grain weight. Grain yield mass expressed on a dry basis was corrected for water content in subsamples obtained from the harvested grain. Harvesting of corn occurred between 26 October and 1 November and soybean between 10 October and 24 October. Plant residue was returned to the plots through the combine using normal machine and harvesting practices. The plots were maintained under a long-term tillage regime consisting of fall chisel plowing (or disk-ripping starting in 2000) and spring cultivation following each corn crop, and no fall plowing or spring cultivation following each soybean crop. Corn stalks were chopped before fall tillage.

## Nitrous Oxide and Carbon Dioxide Fluxes

Soil-to-atmosphere  $\text{N}_2\text{O}$  and  $\text{CO}_2$  fluxes were measured approximately twice per week in April through October of each growing season (2005, 2006, and 2007) using chamber methods described by Venterea et al. (2005, 2006). Fluxes were measured on 39, 29, and 35 separate dates during the 2005, 2006, and 2007 growing seasons, respectively. After 7 May 2007, measurements were stopped in the Sc plots. Fluxes were generally measured between 900 and 1300 h local time when soil temperatures were close to their daily mean. Chamber anchors and tops were fabricated using 20-gauge rectangular stainless steel “steam pans” equipped with a flange around the edges (Superior Products, St. Paul, MN). Anchors were made by cutting out the bottom section of the pan, resulting in a frame measuring 0.50 by 0.29 by 0.086 m deep, which was inserted into the soil so that the flange was nearly flush with the soil surface. Chamber tops (0.50 by 0.29 by 0.102 m high) were fabricated by attaching weatherstrip material (ethylene propylene diene monomer) to the flange to serve as a gasket, covering the outer surfaces with reflective insulation (Reflectix, Markleville, IN), and installing a vent tube (3.5-mm i.d. by 0.15 m long) horizontally on one side and a septum-lined sampling port in the top. The sampling port was connected on the inside of the chamber to a manifold (part no. STCM-13-20/4, Small Parts, Inc., Miramar, FL), which in turn was connected to four sections of fluorinated ethylene propylene tubing (0.8-mm i.d. by 0.2 m long) (Cole Parmer Instrument Co., Vernon Hills, IL) with one section of tubing secured in each quadrant of the chamber.

Fluxes were measured in two locations within each subplot. One chamber anchor was located in the interrow position, between rows with the long side parallel to the row. A second anchor was initially centered on the row (referred to as the row location) with the long side parallel to the row. Once the plant reached a height where it could not be fit inside the chamber without causing damage, the row anchor was moved to just alongside the row. For each measurement, the chamber tops were secured to the anchors with binder clips and gas samples were collected after 0, 0.5, and 1 h using a 12-mL polypropylene syringe. Samples were immediately transferred to 9-mL glass vials sealed with butyl rubber septa (Alltech, Deerfield, IL). Gas samples were analyzed within 1 wk of collection using a headspace autosampler (Teledyne Tekmar, Mason, OH) connected to a gas chromatograph (GC) (Agilent/Hewlett-Packard 5890, Santa Clara, CA) equipped with an electron capture detector for  $\text{N}_2\text{O}$  and a thermal conductivity detector for  $\text{CO}_2$ . The sample vials were maintained under positive pressure until immediately before analysis, which was shown in separate testing using standards to result in negligible leakage after 1 wk of storage at room temperature. The contents of each vial were split to fill two separate gas sample loops so that  $\text{N}_2\text{O}$  and  $\text{CO}_2$  could be measured in a single GC run. The system was calibrated daily using analytical grade standards (Scott Specialty Gases, Troy, MI). Chamber gas concentrations were converted from molar mixing ratio units (ppm) determined by GC analysis to mass per volume units ( $\mu\text{g N m}^{-3}$  and  $\text{mg C m}^{-3}$ ) assuming ideal gas relations using air temperatures measured during sampling.

Gas fluxes were calculated from the rate of change in chamber concentration, chamber volume, and soil surface area using two different flux calculation schemes, linear regression or the nonlinear (quadratic) model of Wagner et al. (1997). For fluxes calculated using the nonlin-

ear scheme, the concentration ratio  $\omega = (C_{0.5} - C_0)/(C_1 - C_{0.5})$  was first calculated, where  $C$  is the chamber  $\text{N}_2\text{O}$  concentration and the subscripts refer to the sampling time (h) after chamber deployment. For cases where  $\omega \leq 1$ , linear regression was used, since this trend violates a fundamental assumption of nonlinear models and because linear regression generates higher flux values for these conditions. Calculated fluxes were also multiplied by a correction factor to account for the so-called “chamber effect” resulting from suppression of the concentration gradient at the soil–atmosphere interface. This effect is known to increase with greater soil air-filled porosity, longer chamber deployment time, and smaller chamber volume/area ratio (Venterea and Baker, 2008). Correction factors were calculated for each sampling date and subplot using techniques based on soil gas transport theory as described by Venterea (2010) and using measurements of soil moisture content and bulk density.

## Soil Properties

Soil temperature was measured during each  $\text{N}_2\text{O}$  flux measurement period using temperature probes (Fisher, Hampton, NH) inserted to the 0.05-m depth within 1 m of the chambers. Air temperature and daily precipitation data were obtained from a weather station 1 km from the site. Soil water content was determined on samples collected to the 0.10-m depth within 1 h of each flux measurement period by drying overnight at 105°C. Additional soil samples were collected for analysis of DOC, pH, inorganic N, and bulk density. Samples were collected on a total of 21 dates: five times in 2005, six times in 2006, and 10 times in 2007. Dissolved organic C was analyzed on 18 of the 21 dates, and pH was analyzed on four dates in 2006 and eight dates in 2007. Following the April 2007 collection, samples from the Sc plots were not collected.

A 19-mm i.d. soil core sampler (Oakfield Apparatus, Oakfield, WI) was used to collect samples at three to six locations from the 0- to 0.10- and 0.10- to 0.20-m depths within each subplot. Sampling locations were randomly selected from within the center 0.38 m of the interrow region, avoiding areas affected by obvious wheel traffic compaction. Cores from each depth were pooled, homogenized, and refrigerated before analysis. Subsamples ( $\sim 8$  g) were extracted with 32 mL of 10 mmol  $\text{L}^{-1}$   $\text{CaCl}_2$ , and extracts were passed through 0.4- $\mu\text{m}$  polycarbonate filters and analyzed for DOC by ultraviolet-persulfate oxidation (Phoenix 8000, Tekmar-Dohrmann, Cincinnati, OH) (Zsolnay, 2003). Soil pH was determined in separate 5-g subsamples mixed with an equal mass of 1 mol  $\text{L}^{-1}$  KCl. Separate 10-g subsamples were extracted in 2 mol  $\text{L}^{-1}$  KCl for 1 h at a soil/liquid ratio of 1:4. After settling for 24 h, extracts were filtered (Whatman no. 42) and stored ( $-20^\circ\text{C}$ ) until analysis. Filtrate samples were analyzed for  $\text{NH}_4^+-\text{N}$  and the sum of  $\text{NO}_2^- - \text{N}$  and  $\text{NO}_3^- - \text{N}$  using a flow-through injection analyzer (Lachat, Loveland, CO). In 2007, samples were also analyzed separately for  $\text{NO}_2^-$  within 24 h of collection by extraction with 2 mol  $\text{L}^{-1}$  KCl adjusted to pH 8, followed by shaking for 10 min, centrifugation at 3000 rpm for 10 min, and flow-through injection analysis with bypass of the Cd reduction column (Stevens and Laughlin, 1995). Bulk density was determined from the total soil mass collected after drying at 105°C. While a relatively small-diameter (19-mm) corer was used to collect samples for bulk density determination, we observed minimal compaction effects, particularly in the upper 0 to 0.1 m, as evidenced by the

length of the actual samples relative to the sampled depth. Bulk density values interpolated between sampling dates were used to estimate water-filled pore space (WFPS) in the upper 0 to 0.10 m and for determining flux-calculation correction factors.

## Data Analysis and Statistics

For each sampling date, a mean  $N_2O$  flux for each subplot was determined from the arithmetic mean of measurements made at the inter-row and row locations. This mean flux was used to determine the total growing-season  $N_2O$  and  $CO_2$  emissions by trapezoidal integration with the assumption that mean daily fluxes changed linearly between measurement dates. For  $N_2O$ , separate calculations of time-integrated emissions were made using daily fluxes calculated using each of the four flux-calculation schemes, i.e., using linear regression and the quadratic model, each with and without correction for chamber-induced errors. Fluxes of  $N_2O$  were converted to greenhouse gas units ( $CO_2$  equivalents) using the 100-yr horizon global warming potential of 298 (Forster et al., 2007). Effects of the chamber position on flux were examined using ANOVA within each crop, fertilizer, and year, with position as the main factor and sampling date as the split factor. Effects of crop and fertilizer on the total growing-season  $N_2O$  and  $CO_2$  emissions, grain yields, and soil properties at each depth interval were evaluated with crop as the main factor, fertilizer as the split factor, and year (or sampling date for soil properties) as the split-split factor. Soybean and corn grain yields were evaluated separately. For total emissions and soil properties, separate ANOVAs were performed on two separate data sets: (i) data from 2005 and 2006 (and April 2007 for soil properties) that included all three crops; and (ii) data from 2005, 2006, and 2007 that included only the Cc and Cs crops. An ANOVA was performed using the GLM procedure in SAS (SAS Institute, 2003), with appropriate error terms

defined according to the designs described above. Means separation was done using LSD, with LSD values calculated manually for the appropriate level of comparison and significance criteria of  $P < 0.05$  (Gomez and Gomez, 1984).

## RESULTS

### Climate Factors

Air temperature and precipitation during the three growing seasons were similar (Fig. 1a). Approximately 13% less precipitation was recorded during 1 Apr. through 1 Oct. 2006 than during the same periods in 2005 and 2007. There were no significant differences in soil moisture or temperature at the time of  $N_2O$  flux sampling due to crop or fertilizer management (Fig. 1b and 1c). Soil WFPS never exceeded 85%, and declined to as low as 20% during warm and dry periods in July of 2006 and 2007.

### Nitrous Oxide and Carbon Dioxide Emissions

For all three growing seasons, the maximum mean daily  $N_2O$  fluxes occurred in the corn subplots that were fertilized with AA (Fig. 2a and 2b). The AA-fertilized treatments also displayed consistent temporal trends characterized by fluxes that increased and reached a maximum within 4 to 6 wk following fertilizer application, and then decreased to preapplication levels. The U-fertilized corn plots also displayed elevated  $N_2O$  fluxes following fertilizer application, but the temporal patterns were more erratic and the periods of elevated fluxes more short-lived compared with AA. Mean daily  $N_2O$  fluxes in the soybean plots were relatively uniform with time (Fig. 2c) and never exceeded  $80 \mu g N m^{-2} h^{-1}$  compared with maximum fluxes of approximately 350 and  $320 \mu g N m^{-2} h^{-1}$  in the AA- and U-fertilized

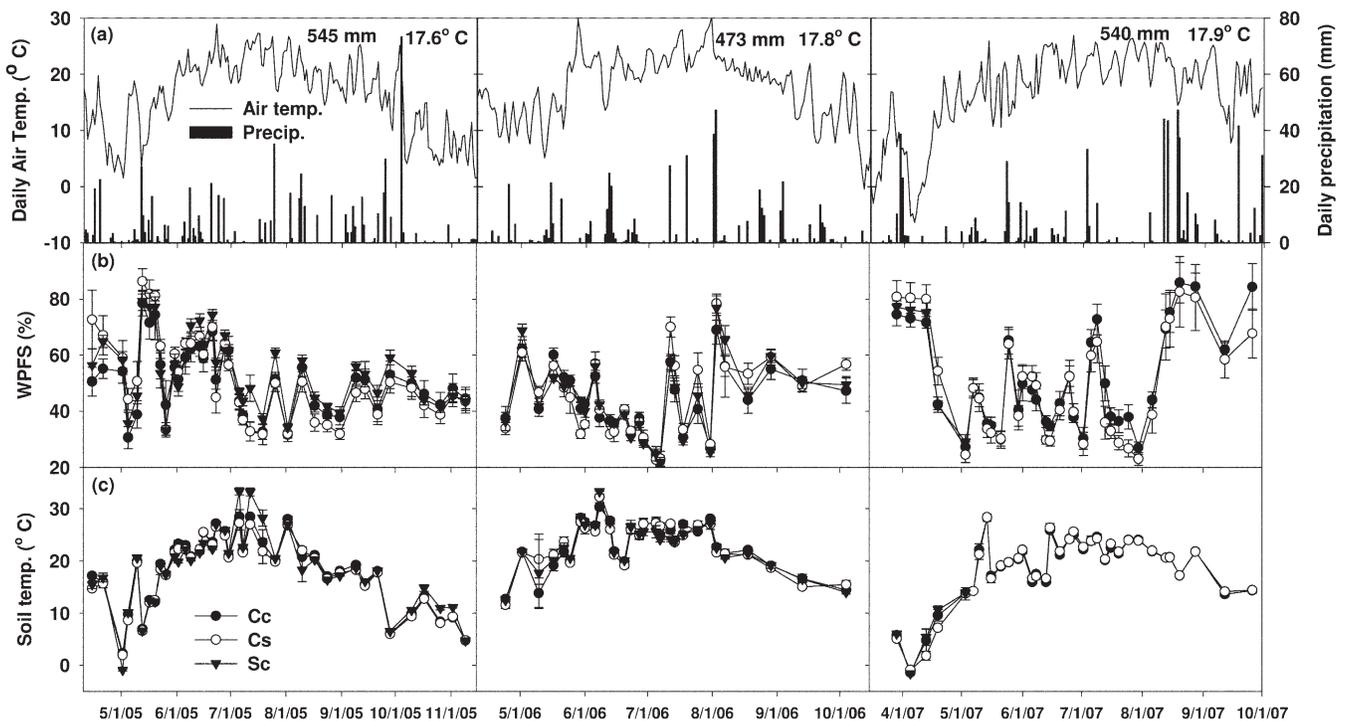


Fig. 1. (a) Daily air temperature (left axis) and precipitation (right axis), (b) water-filled pore space (WFPS), and (c) soil temperature in plots managed under corn after corn (Cc), corn after soybean (Cs), and soybean after corn (Sc) during the 2005, 2006, and 2007 growing seasons. Values shown in (a) are average daily temperature and total precipitation for the period 1 April through 1 October of each year.

corn plots, respectively. The general trend in soil CO<sub>2</sub> emissions was an increase as the season progressed, followed by a decline as temperatures decreased (Fig. 3). Declines in CO<sub>2</sub> emissions were also observed during warm and dry periods in July 2006 and 2007, and a sharp increase was observed following significant rainfall in Aug 2007. Emissions of CO<sub>2</sub> tended to be higher in Cc than Cs or Sc, with no evident fertilizer trends.

Total time-integrated N<sub>2</sub>O emissions displayed significant differences by both fertilizer and crop (Table 1; Fig. 4a). During 2005 to 2006, emissions were lower in the unfertilized Sc crop than in Cc or Cs, as expected. There was no apparent residual effect of fertilizer applied in the previous growing season on N<sub>2</sub>O emissions from Sc. During the entire study (2005–2007), N<sub>2</sub>O emissions with AA fertilizer were approximately double the emissions with U, with no difference between Cc and Cs. The only exception to the trend of higher emissions with AA was that similar N<sub>2</sub>O emissions were observed in the Cc-A and Cc-U treatments in 2005, which resulted in a significant fertilizer × season interaction (*P* = 0.031).

Total time-integrated CO<sub>2</sub> emissions displayed significant differences by crop, with approximately 20% higher emissions observed in Cc than in Cs or Sc (Table 1; Fig. 4b). There were no differences in CO<sub>2</sub> emissions between Cs and Sc, and no differences by fertilizer source. In contrast to N<sub>2</sub>O, which displayed no significant variation in emissions across growing seasons, CO<sub>2</sub> emissions were significantly higher in 2005 (overall mean = 4.8 Mg C h<sup>-1</sup>) compared with 2006 emissions (4.1 Mg C h<sup>-1</sup>), which in turn were higher than in 2007 (3.7 Mg C h<sup>-1</sup>). Both

2006 and 2007 experienced periods of very dry conditions, which were accompanied by sharp declines in CO<sub>2</sub> emissions during the middle of the growing season.

Fluxes of N<sub>2</sub>O from chambers positioned in the interrow vs. row did not show any consistent trends and generally did not differ significantly (data not shown). The only exception was in the Cc-U treatment in 2005, where N<sub>2</sub>O fluxes in the row position (mean = 39.7 μg N m<sup>-2</sup> h<sup>-1</sup>) were higher than in the interrow (23.0 μg N m<sup>-2</sup> h<sup>-1</sup>), possibly due to greater root-derived C inputs closer the row. We expected fluxes from interrow positions in AA-fertilized subplots to be higher than in row positions, but this trend was not found. This was probably due to the fact that AA was applied several days before planting and apparently the rows were not always planted so that the AA injection path was centered between the rows. Fluxes of CO<sub>2</sub> were generally higher in the row position across most treatments and years. Mean row CO<sub>2</sub> fluxes were 110, 131, and 117 mg C m<sup>-2</sup> h<sup>-1</sup> compared with interrow fluxes of 89, 108, and 92 mg C m<sup>-2</sup> h<sup>-1</sup> during 2005, 2006, and 2007, respectively.

Using the N<sub>2</sub>O emissions data from the Cc, Cs, and Sc treatments during 2005 to 2007, aggregated growing-season emissions for a 2-yr C/S rotation at this site were estimated at 1.37 and 0.80 kg N ha<sup>-1</sup> with AA and U fertilizers, respectively, compared with emissions in a C/C system of 2.15 and 1.01 kg N ha<sup>-1</sup> with AA and U, respectively (Table 2). Thus, a shift from C/S to C/C would be expected to result in an increase in growing-season emissions of 0.78 kg N ha<sup>-1</sup> (equivalent to 0.11 Mg C ha<sup>-1</sup>

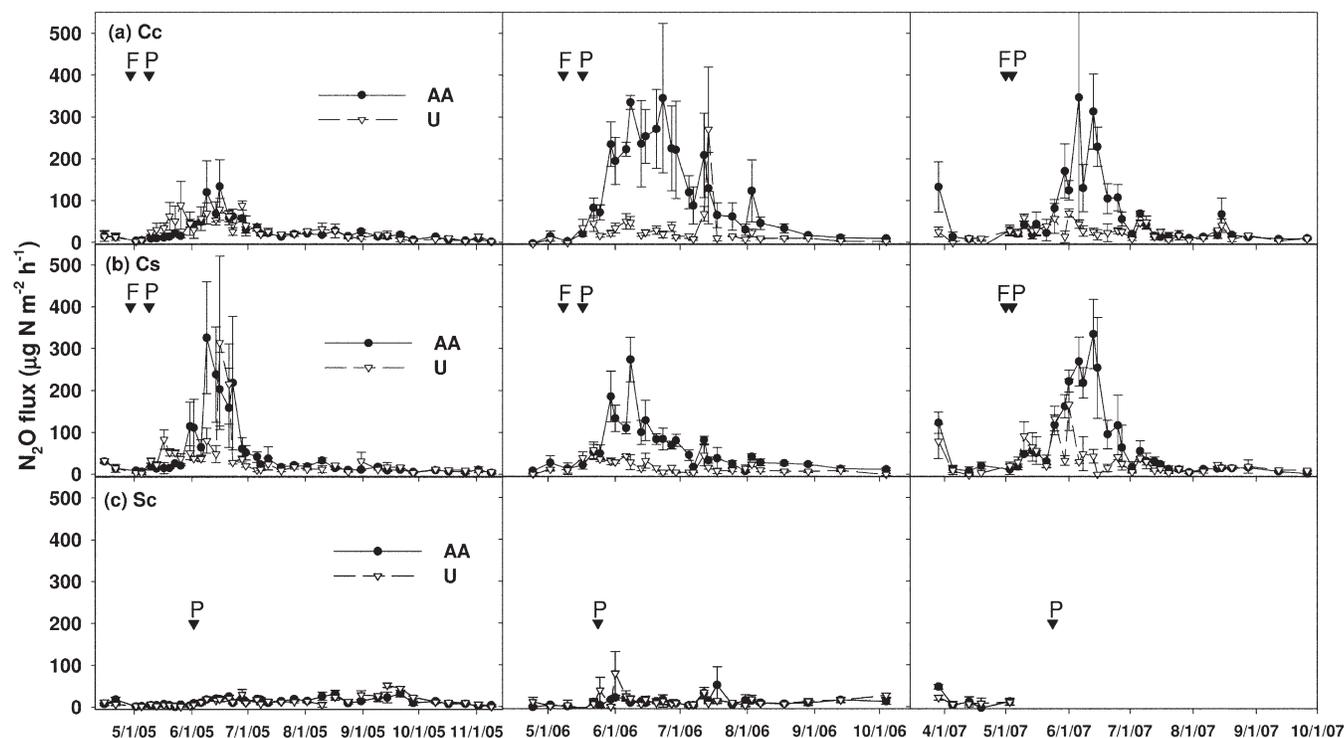


Fig. 2. Soil N<sub>2</sub>O fluxes in plots managed under (a) corn after corn (Cc), (b) corn after soybean (Cs) and (c) soybean after corn (Sc) during the 2005, 2006, and 2007 growing seasons, and fertilized with anhydrous NH<sub>3</sub> (AA) or urea (U). For Sc, fertilizer designations apply to the previous season. Inverted triangles indicate dates of fertilizer application (F) and planting (P). Symbols are means with standard error bars. Fluxes were calculated using the quadratic model and corrected for chamber effects.

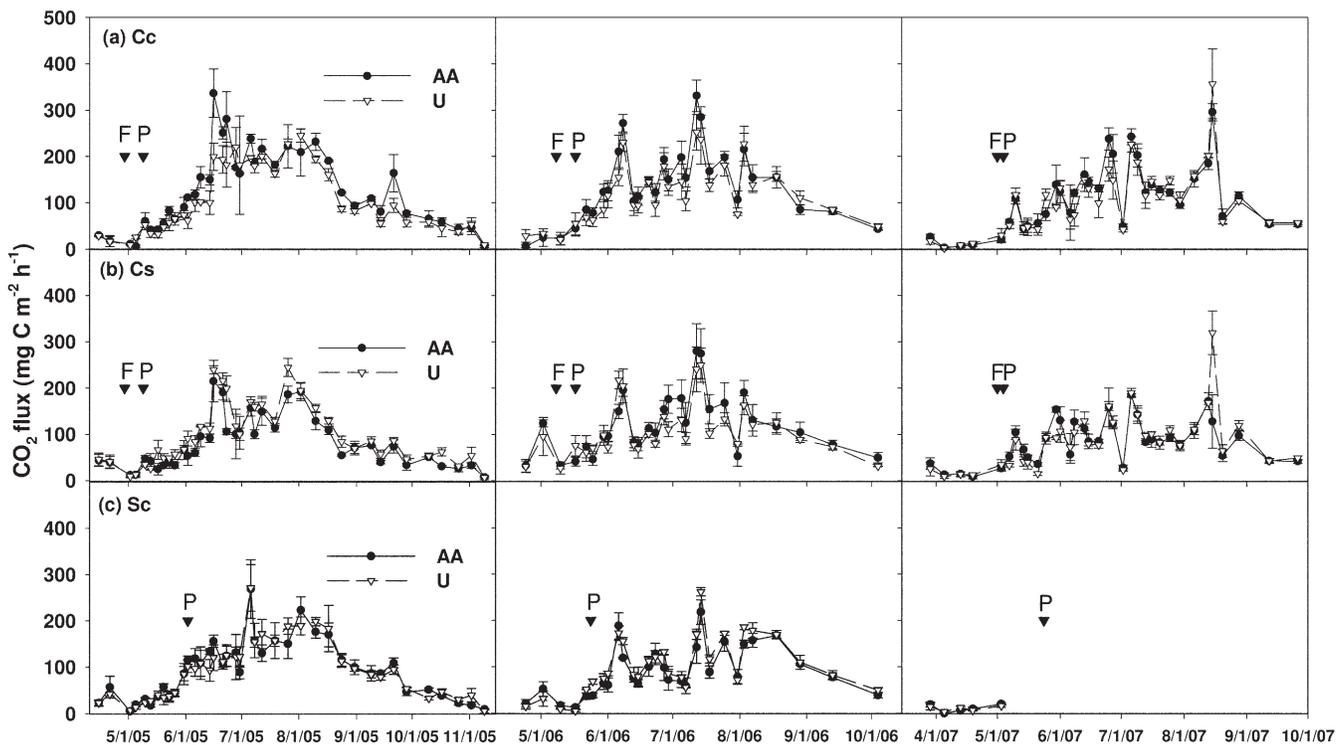


Fig. 3. Soil CO<sub>2</sub> fluxes in plots managed under (a) corn after corn (Cc), (b) corn after soybean (Cs) and (c) soybean after corn (Sc) during the 2005, 2006, and 2007 growing seasons, and fertilized with injected anhydrous NH<sub>3</sub> (AA) or urea (U). For Sc, fertilizer designations apply to the previous season. Inverted triangles indicate dates of fertilizer application (F) and planting (P). Symbols are means with standard error bars. Fluxes were calculated using the quadratic model and corrected for chamber effects.

as CO<sub>2</sub>) with AA, compared with only 0.21 kg N ha<sup>-1</sup> (or 0.03 Mg C ha<sup>-1</sup>) with U.

Results shown in Table 2 also show how different flux-calculation schemes generated different time-integrated emissions estimates. Without correcting for chamber-induced errors, the quadratic flux-calculation model resulted in growing-season emissions estimates that were, on average, about 20% higher than linear regression-based estimates. Application of correction factors for chamber-induced errors increased the estimates, on average, by 22 and 8% compared with uncorrected fluxes determined using the linear and quadratic schemes, respectively. Estimates

**Table 1. Analysis of variance results (*P* values) examining the effects of crop (C), fertilizer (F), and growing season (S) on soil N<sub>2</sub>O and CO<sub>2</sub> emissions and grain yields in plots managed under corn after corn (Cc), corn after soybean (Cs), or soybean after corn (Sc).**

Factors	<i>P</i> value					
	2005–2006† (Cc, Cs, Sc)			2005–2007§ (Cc, Cs)		
	N <sub>2</sub> O	CO <sub>2</sub>	Yield‡	N <sub>2</sub> O	CO <sub>2</sub>	Yield
C	0.011	0.0011	0.039	0.23	0.0023	0.056
F	0.0022	0.64	0.021	<0.001	0.48	0.048
S	0.76	<0.001	<0.001	0.74	<0.001	<0.001
C × F	0.017	0.19	0.57	0.20	0.16	0.56
C × S	0.044	0.080	0.00031	0.073	0.094	0.018
F × S	0.019	0.64	0.70	0.031	0.46	0.98
C × F × S	0.055	0.070	0.039	0.26	0.068	0.51

† Analyses performed on data collected from the Cc, Cs, and Sc crops in 2005 and 2006.

‡ Soybean yields were not included in this analysis.

§ Analyses performed on data collected from the Cc and Cs crops in 2005, 2006, and 2007.

based on the corrected quadratic scheme were, on average, 28% higher than the uncorrected linear scheme, ranging from 23% higher in the Cc-U and Cs-U treatments to 32 and 35% higher in the Cs-A and Cc-A treatments, respectively. The quadratic flux-calculation scheme in most cases tended to generate higher variability in time-integrated emissions estimates as measured by the CV (Table 3).

## Grain Yields

On average during 2005 to 2007, corn grain yields were 10% higher in the U- than the AA-fertilized subplots (combined for Cs and Cc) and this difference was significant ( $P = 0.048$ ) (Fig. 4c; Table 1). On average during 2005 to 2007, corn grain yields were 14% higher in the Cs than the Cc cropping system (combined for AA and U), but this difference was not significant ( $P = 0.056$ ). The greatest difference in yields between Cc and Cs was observed in 2006, while yields in Cc and Cs during 2005 and 2007 were more similar, which resulted in a significant crop × season interaction effect ( $P = 0.018$ ). Mean soybean yields were significantly higher in 2006 (3.2 Mg ha<sup>-1</sup>) than 2005 (2.3 Mg ha<sup>-1</sup>) and did not differ by fertilizer treatment applied to the corn phase in the preceding year.

## Soil Chemistry

Soil DOC concentrations varied significantly by both crop and fertilizer treatment, with significant crop × date and fertilizer × date interactions (Fig. 5 and 6; Table 4). The

most consistent effect was that higher DOC was observed with AA. This effect was strongest in the Cc and Cs crops at the 0.1- to 0.2-m depth (Fig. 6a and 6b). There was also evidence, however, that AA application during the previous growing season resulted in higher DOC in the Sc treatment for the 0- to 0.1-m depth, although this result was strongly influenced by elevated DOC levels observed on one sampling date (15 June 2005) (Fig. 5c). For 2005 and 2006, the mean DOC at the shallower depth in Sc (8.8 mg C kg<sup>-1</sup>) was also significantly lower than in Cs (9.8 mg C kg<sup>-1</sup>) or Cc (10.7 mg C kg<sup>-1</sup>), which did not differ significantly from each other (Fig. 5).

As expected, soil NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> levels tended to be higher in the fertilized (Cc and Cs) crops than in Sc (Tables 4 and 5); however, in the Sc treatments during summer 2006, NH<sub>4</sub><sup>+</sup> concentrations >100 mg N kg<sup>-1</sup> (at 0.1–0.2 m in the AA treatment) and NO<sub>3</sub><sup>-</sup> concentrations >10 mg N kg<sup>-1</sup> (at 0–0.1 m in AA and U treatments) were observed (data not shown). Thus, the differences for these cases were not significant. There were no significant differences in inorganic N between Cc and Cs. Thus, there was no evidence that N<sub>2</sub> fixation by soybean in the previous season affected soil inorganic N levels in the Cs crop during the subsequent growing season. There were differences by fertilizer: NH<sub>4</sub><sup>+</sup> (at 0–0.1 m) and NO<sub>3</sub><sup>-</sup> (at 0.1–0.2 m) were greater in the AA- than the U-fertilized corn plots (Tables 4 and 5).

Soil NO<sub>2</sub><sup>-</sup> concentrations measured in Cc and Cs in 2007 were <0.10 mg N kg<sup>-1</sup> in all samples from the U-fertilized treatments. Higher levels were found in the AA-fertilized treatments, with peak NO<sub>2</sub><sup>-</sup> concentrations in the range of 2 to 3 mg N kg<sup>-1</sup> detected in the 13 June 2007 sampling, with no significant differences between Cc and Cs. Soil pH measured in 1 mol L<sup>-1</sup> KCl extracts tended to be lower in Cc than Cs or Sc, but the differences were not significant (*P* > 0.096) across the entire data set. The mean soil pH for Cc, Cs, and Sc was 5.24, 5.82, and 5.78 at 0 to 0.1 m, and 5.47, 5.73, and 5.65 at 0.1 to 0.2 m. There were no pH differences by fertilizer source.

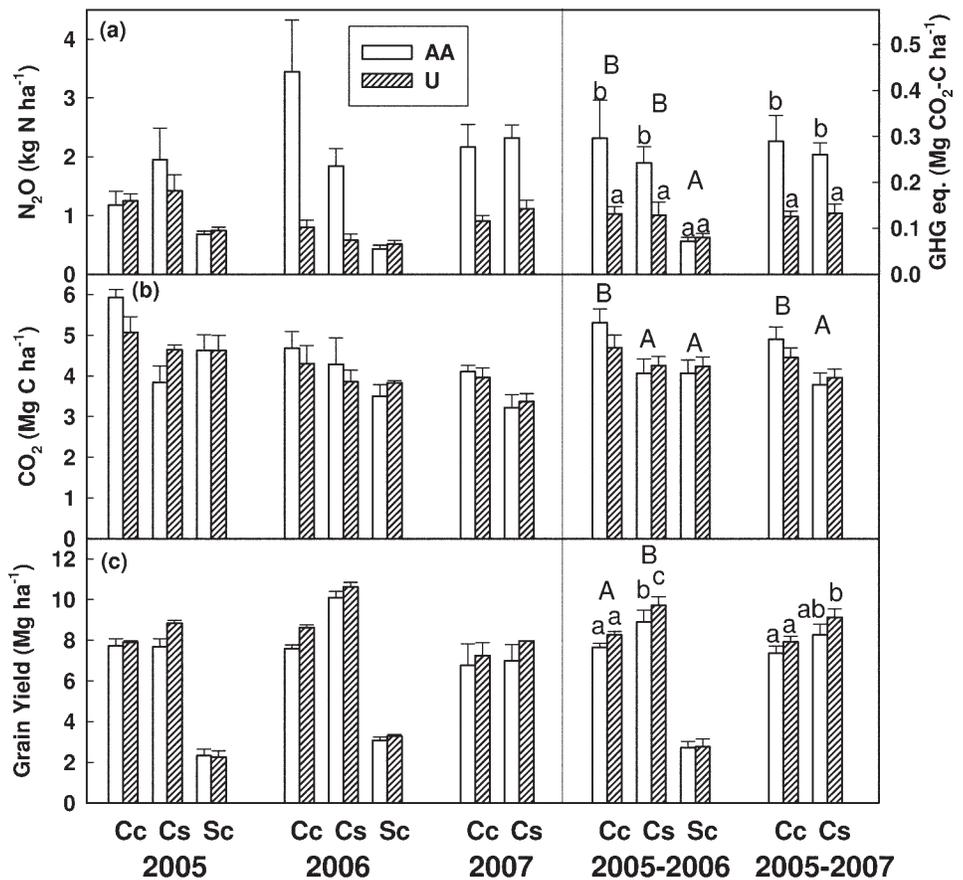


Fig. 4. Total growing season soil emissions of (a) N<sub>2</sub>O and (b) CO<sub>2</sub>, and (c) grain yields in plots managed under corn after corn (Cc), corn after soybean (Cs), and soybean after corn (Sc), and fertilized with anhydrous NH<sub>3</sub> (AA) or urea (U). For Sc, fertilizer designations apply to the previous season. Emissions are based on fluxes calculated using the quadratic model and corrected for chamber effects. Within each of 2005–2006 and 2005–2007, bars having the same lowercase letters are not significantly different. Uppercase letters indicate significant differences by crop across both fertilizer treatments (*P* < 0.05). Yield comparisons are shown for corn only. Bars are means with standard error bars.

## DISCUSSION

### Rotation Effects

In research plots in southeastern Minnesota after more than 15 yr of management, N<sub>2</sub>O emissions averaged across three consecutive growing seasons from C/C systems were nearly identical

Table 2. Aggregated growing-season N<sub>2</sub>O emissions for a 2-yr corn–soybean (C/S) rotation compared with continuous corn (C/C), with the corn phase fertilized using anhydrous NH<sub>3</sub> (AA) or urea (U). Different estimates are shown for linear regression and quadratic flux-calculation schemes, with and without correction for chamber-induced errors.

System	Fertilizer	Growing-season N <sub>2</sub> O emissions			
		Linear regression		Quadratic model	
		Uncorrected	Corrected	Uncorrected	Corrected
— kg N ha <sup>-1</sup> —					
Cct	AA	1.59	1.98	1.96	2.15
	U	0.82	0.98	0.95	1.01
C/S‡	AA	1.04	1.29	1.26	1.37
	U	0.65	0.79	0.75	0.80

† Values determined from the mean growing season emissions in all corn crops receiving AA or U fertilizer during 2005–2007.

‡ Values determined by aggregating the mean growing season emissions in the soybean crop during 2005–2006 with the mean growing season emissions in all corn crops receiving AA or U fertilizer during 2005–2007.

**Table 3. Coefficients of variation in growing season N<sub>2</sub>O emissions in plots managed under corn after corn (Cc), corn after soybean (Cs), or soybean after corn (Sc), and fertilized with anhydrous NH<sub>3</sub> (AA) or urea (U) based on fluxes calculated using linear regression and quadratic flux-calculation schemes, with and without correction for chamber-induced errors.**

Crop	Fertilizer	Coefficients of variation			
		Linear regression		Quadratic model	
		Uncorrected	Corrected	Uncorrected	Corrected
%					
Cct	AA	60.5	61.7	56.8	57.7
	U	24.1	25.2	25.3	26.6
Cst	AA	28.8	27.9	29.8	29.8
	U	42.6	41.6	44.4	44.6
Sc†	AA	25.6	25.7	27.5	29.1
	U	20.2	20.7	24.2	24.9

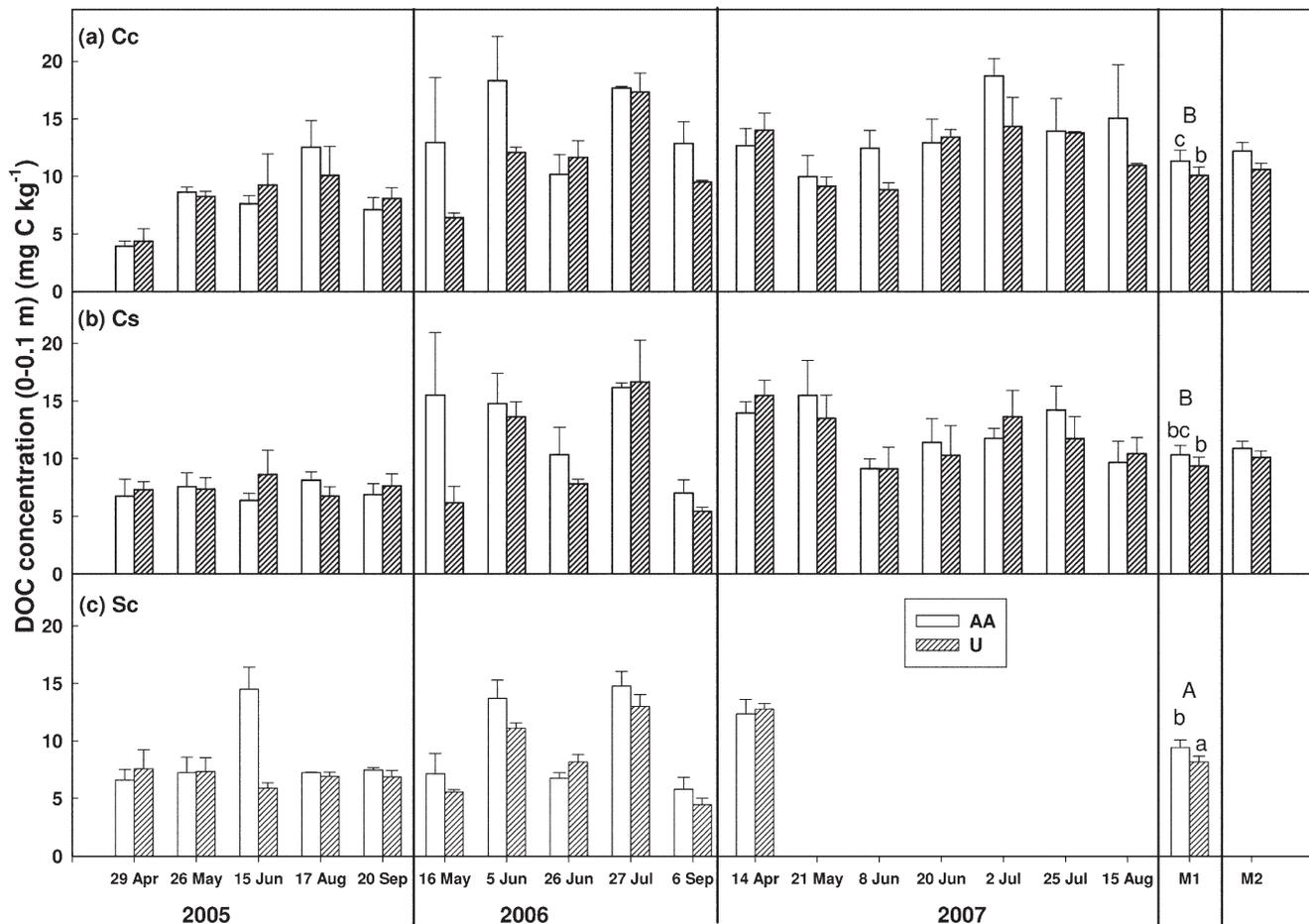
† Determined from growing-season emissions obtained for three replications of each treatment combination during each of 2005, 2006, and 2007 (*n* = 9).

‡ Determined from growing-season emissions obtained for three replications of each treatment combination during each of 2005 and 2006 (*n* = 6).

to emissions from C/S. These results differ from those of Drury et al. (2008), who observed that N<sub>2</sub>O emissions averaged across three consecutive growing seasons in C/C were approximately twice as high as emissions from the corn phase of C/S. Data re-

ported by Drury et al. (2008) were measured within 4 yr of establishing conventionally managed cropping systems in southwest Ontario, Canada, that were fertilized with 170 kg N ha<sup>-1</sup> applied mainly as post-plant sidedress urea-NH<sub>4</sub>NO<sub>3</sub> (UAN). Our results also differ from those of Mosier et al. (2006), who found the opposite result, i.e., higher N<sub>2</sub>O emissions from C/S within 3 yr of establishing no-till, irrigated cropping systems in northeast Colorado. Mosier et al. (2006) found that annual N<sub>2</sub>O emissions from unfertilized corn following soybean were 2.6 to 3.8 times higher than corn after corn. Mosier et al. (2006) also found that N<sub>2</sub>O emissions were 50 to 70% higher in Cs than Cc treatments when corn was fertilized with 202 to 224 kg N ha<sup>-1</sup> as UAN applied by injection before planting. In the studies mentioned above, and in the current study, the C/C systems and the corn phase of the C/S systems were managed with the same N fertilizer inputs.

Thus, it appears that in Drury et al. (2008), higher N<sub>2</sub>O emissions in the C/C system were driven by higher annual inputs of crop residue from corn, together with residual fertilizer-derived



**Fig. 5. Soil dissolved organic C (DOC) concentrations in samples from the 0- to 0.1-m depth in plots managed under (a) corn after corn (Cc), (b) corn after soybean (Cs), and (c) soybean after corn (Sc), and fertilized with anhydrous NH<sub>3</sub> (AA) or urea (U). For Sc, fertilizer designations apply to the previous season; M1 indicates means for all sampling dates (Cc, Cs, and Sc) up to and including 16 Apr. 2007, M2 indicates means for all sampling dates (Cc and Cs only). Within each of M1 and M2, individual bars having the same lowercase letters are not significantly different. Uppercase letters indicate significant differences by crop across both fertilizer treatments (*P* < 0.05). Bars are means with standard error bars.**

N, which may have carried over to the subsequent growing season. In contrast, it appears that in Mosier et al. (2006), a smaller amount of lower C/N ratio residue from soybean resulted in higher N<sub>2</sub>O emissions in the C/S system. Neither study, however, reported soil inorganic N or DOC data. Therefore, it is difficult to explain the contrasting results. In the current study, DOC and inorganic N levels in the upper 0.2 m of the soil profiles of the Cc and Cs treatments did not differ, based on approximately 20 measurement dates during three growing seasons. It is possible that differences in tillage practices among the studies may have been partly responsible for the different results, although a probable mechanism is not clear. Tillage in the current study included fall chisel plowing following corn, which was done annually in the C/C system and biennially in the C/S system, with no fall tillage following the soybean phase of the rotation. This tillage regime is intermediate in intensity between that used by Drury et al. (2008), which included annual fall chisel plowing following both corn and soybean, and Mosier et al. (2006) who used no-till management.

While both Drury et al. (2008) and Mosier et al. (2006) found no significant difference in CO<sub>2</sub> emissions between Cc and Cs treatments, we found approximately 20% higher

CO<sub>2</sub> emissions from Cc. Our CO<sub>2</sub> results are consistent with Omonode et al. (2007) and Wilson and Al-Kaisi (2008), who each found 16 to 18% higher mean CO<sub>2</sub> emissions from Cc during two growing seasons in research plots in Indiana and Iowa, respectively. It has been hypothesized that increased soil respiration in monoculture corn cropping systems may compensate for higher biomass inputs, resulting in no significant increase in soil C accumulation compared with C/S rotations (West and Post, 2002). Our CO<sub>2</sub> data are consistent with this idea.

Any estimate of growing-season trace gas emissions based on noncontinuous chamber data suffers from a lack of information regarding fluxes occurring between measurement dates. Parkin (2008) estimated that chamber sampling frequencies used in the current study (i.e., twice per week) resulted in a >70% probability of estimating actual emission rates within ±10%. A previous study in the same soil showed that short-term N<sub>2</sub>O flux responses to rainfall events during the growing season were relatively small, and that this was probably due to the well-drained conditions (Venterea et al., 2005). Thus, we believe that the emissions estimates reported here are reasonably accurate within the inherent limitations of the chamber method used.

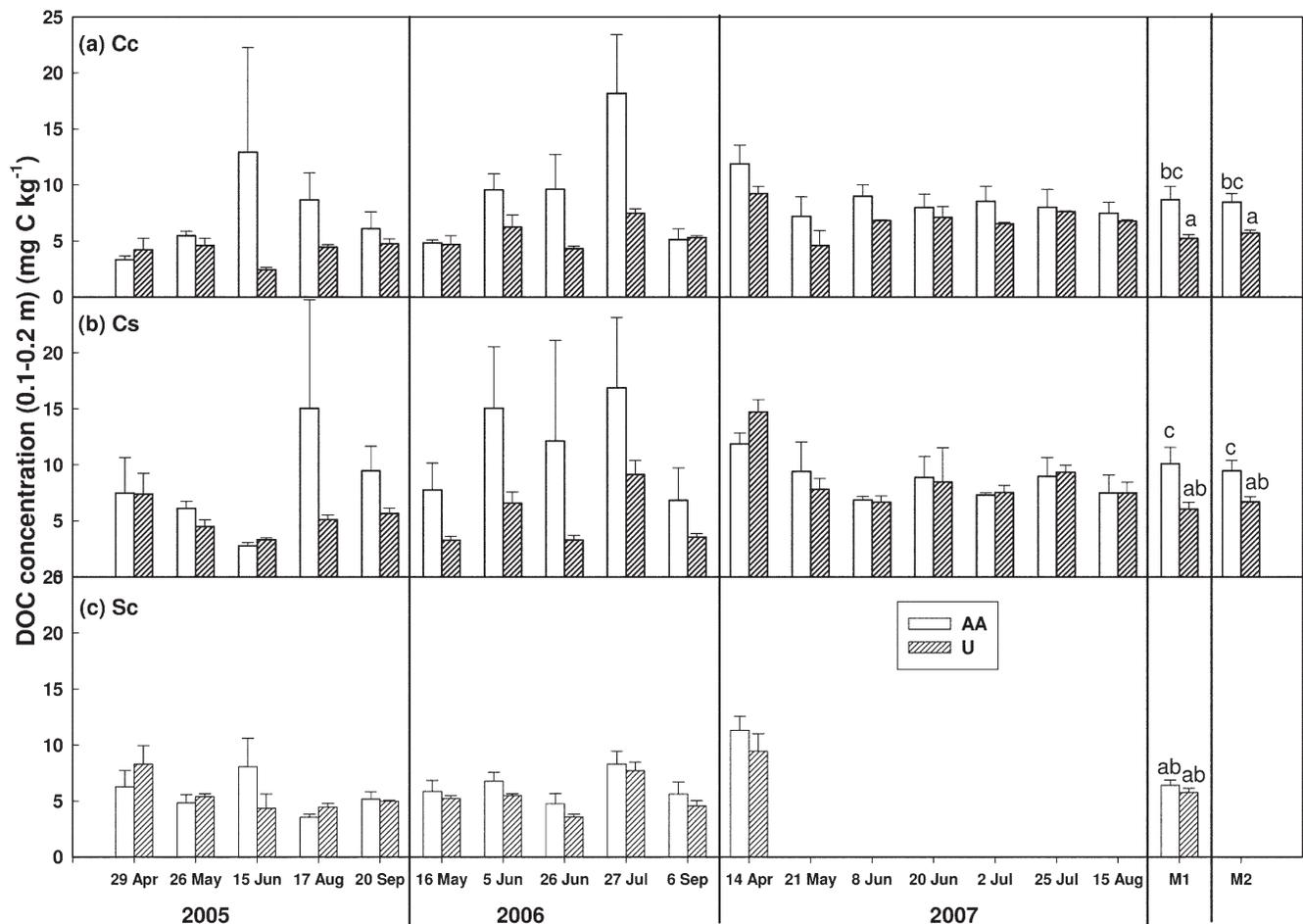


Fig. 6. Soil dissolved organic C (DOC) concentrations in samples from the 0.1- to 0.2-m depth in plots managed under (a) corn after corn (Cc), (b) corn after soybean (Cs), and (c) soybean after corn (Sc), and fertilized with anhydrous NH<sub>3</sub> (AA) or urea (U). For Sc, fertilizer designations apply to the previous season; M1 indicates means for all sampling dates (Cc, Cs, and Sc) up to and including 16 April 2007, M2 indicates means for all sampling dates (Cc and Cs only). Within each of M1 and M2, individual bars having the same lowercase letters are not significantly different ( $P < 0.05$ ). Bars are means with standard error bars.

**Table 4. Results of analysis of variance (*P* values) examining the effects of crop (C), fertilizer (F), and sampling date (D) on soil properties for the 0.0- to 0.1- and 0.1- to 0.2-m depth intervals in plots planted to corn after corn (Cc), corn after soybean (Cs), or soybean after corn (Sc).**

Factor	<i>P</i> value							
	NH <sub>4</sub> -N		NO <sub>3</sub> -N		DOC†		pH	
	0-0.1	0.1-0.2	0-0.1	0.1-0.2	0-0.1	0.1-0.2	0-0.1	0.1-0.2
	<i>Cc, Cs, Sc‡</i>							
C	0.044	0.43	0.014	0.28	0.049	0.11	0.13	0.29
F	0.018	0.43	0.78	0.041	0.0043	0.010	0.16	0.41
D	<0.001	0.0023	<0.001	0.0051	<0.001	<0.001	<0.001	<0.001
C × F	0.12	0.57	0.96	0.29	0.87	0.21	0.74	0.88
C × D	0.19	0.40	<0.001	0.58	0.027	0.59	0.13	0.034
F × D	0.0081	0.97	0.017	0.0094	0.024	0.30	0.19	0.22
C × F × D	0.75	0.23	0.88	0.52	0.26	0.78	0.42	0.49
	<i>Cc, Cs§</i>							
C	0.59	0.60	0.59	0.85	0.40	0.27	0.096	0.19
F	0.018	0.68	0.42	0.035	0.079	0.024	0.75	0.25
D	<0.001	<0.001	<0.001	0.0013	<0.001	0.001	<0.001	<0.001
C × F	0.44	0.72	0.99	0.80	0.50	0.78	0.28	0.42
C × D	0.99	0.21	0.79	0.99	0.058	0.82	0.27	0.87
F × D	0.0011	0.49	0.0084	0.0021	0.16	0.37	0.17	0.64
C × F × D	0.99	0.73	0.99	0.98	0.91	0.72	0.86	0.86

† Dissolved organic C.

‡ Analyses performed on data from the Cc, Cs, and Sc crops for April 2005 through April 2007.

§ Analyses performed on data from the Cc and Cs crops for April 2005 through October 2007.

A limitation of this study, as well as Drury et al. (2008), is the absence of measurements during interseasonal periods, i.e., approximately November through March. It is possible that N<sub>2</sub>O fluxes during thaw events may have been influenced by crop residue effects to a greater extent than emissions during the subsequent growing season, and therefore could alter

because both temporal and spatial dynamics can be extraordinarily high due to highly variable soil temperature and liquid water contents across the scales of hours and centimeters (Dörsch et al., 2004).

**Table 5. Concentrations of NH<sub>4</sub>- and NO<sub>3</sub>-N in soils collected from the 0- to 0.1 and 0.1- to 0.2-m depths in plots managed under corn after corn (Cc), corn after soybean (Cs), or soybean after corn (Sc), and fertilized with anhydrous NH<sub>3</sub> (AA) or urea (U). For Sc, fertilizer designations apply to the previous season.†**

Crop	Fertilizer	NH <sub>4</sub> -N		NO <sub>3</sub> -N	
		0-0.1 m	0.1-0.2 m	0-0.1 m	0.1-0.2 m
mg N kg <sup>-1</sup>					
<i>Cc, Cs, Sc‡</i>					
Cc	AA	35 (16) b	B 19 (7.8)	26 (7.4)	B 35 (10) b
	U	5.7 (1.6) a	13 (6.3)	27 (5.1)	6.3 (0.90) a
Cs	AA	24 (9.3) ab	B 23 (14)	24 (5.9)	B 39 (14) b
	U	9.1 (2.2) a	27 (14)	21 (4.0)	5.7 (0.90) a
Sc	AA	2.5 (0.34) a	A 21 (11)	7.0 (1.1)	A 4.7 (0.66) a
	U	1.6 (0.13) a	4.8 (3.2)	5.7 (0.70)	3.5 (0.33) a
<i>Cc, Cs§</i>					
Cc	AA	24 (9.8) b	15 (4.9)	28 (5.0)	35 (6.4) b
	U	4.8 (1.1) a	8.1 (3.8)	25 (3.2)	6.7 (0.85) a
Cs	AA	19 (5.8) ab	17 (3.8)	25 (4.0)	31 (7.9) b
	U	6.4 (1.4) a	16 (8.6)	21 (2.6)	7.1 (1.3) a

† Within each column and crop comparison, values with the same lowercase letter are not significantly different. Uppercase letters to the right of each pair of values indicate significant differences by crop (*P* < 0.05).

‡ Mean (and standard error) of samples from the Cc, Cs, and Sc crops during April 2005 through April 2007.

§ Mean (and standard error) of samples from the Cc and Cs crops during April 2005 through Oct 2007.

the C/C vs. C/S comparison. Mosier et al. (2006) did make year-round chamber measurements and found no difference in N<sub>2</sub>O emissions between cropping systems during interseasonal periods. Using micrometeorological methods, Wagner-Riddle et al. (2007) and Wagner-Riddle and Thurtell (1998) found no consistent trends in non-growing-season, thaw-induced emissions following corn and soybean production, i.e., in some cases fluxes following corn were higher and in other cases fluxes following soybean were higher or not different. We did measure thaw-induced N<sub>2</sub>O emissions during the winters of 2005 and 2006 using chambers, but only following the corn phase of the C/S rotation (data not shown). In both years, we measured peak daily mean emissions in the range of 125 to 175 μg N m<sup>-2</sup> h<sup>-1</sup>. Estimating total (i.e., time-integrated) emissions during thaw periods is particularly problematic using chambers

## Fertilizer Effects

Early studies showed that AA application can lead to high N<sub>2</sub>O emissions relative to other fertilizers (Bremner et al., 1981). Since then, however, there have been only a few direct comparative studies in this regard. In contrast to the current study and others showing elevated N<sub>2</sub>O emissions with AA (Venterea et al., 2005; Thornton et al., 1996), a recent study in south-central Canada showed little or no difference in N<sub>2</sub>O emissions from two black Chernozem soils fertilized with spring-applied U vs. AA (Burton et al., 2008). It is likely that the effects of fertilizer form will be site specific and depend to some extent on soil pH. Nitrification-mediated reactions involving NO<sub>2</sub><sup>-</sup>, which are promoted at lower pH, have been implicated in promoting N<sub>2</sub>O emissions with AA (Venterea and Rolston, 2000; Venterea, 2007). We originally hypothesized that the generally lower pH in the Cc soil, together with the expected presence of NO<sub>2</sub><sup>-</sup> following AA, would result in higher N<sub>2</sub>O emissions in Cc-AA than Cs-AA, but no crop × fertilizer interaction was found (*P* > 0.20). We did find higher NO<sub>2</sub><sup>-</sup> levels with AA than U. While NO<sub>2</sub><sup>-</sup> accumulation following U application can also occur, it is more likely when U is banded or applied as UAN (Mulvaney et al., 1997).

The elevated DOC levels found here with AA are also consistent with previous studies that have attributed this effect to the dissolution of organic matter resulting from the elevation of pH during AA hydrolysis (Clay et al., 1995; Mulvaney et al., 1997). In laboratory incubations, Mulvaney et al. (1997) found that soil amendment with both AA and U resulted in elevated DOC levels. To the best of our knowledge, the current study is the first to compare fertilizer effects on DOC at the field scale. It cannot be definitively stated that the increase in DOC observed here with AA contributed to the higher N<sub>2</sub>O emissions, because the relative role of nitrification vs. denitrification in driving N<sub>2</sub>O emissions is not clear. The possible importance of nitrification is suggested by the observations that some of the highest N<sub>2</sub>O fluxes were measured during periods when the WFPS was <50%, and that the peak in soil NO<sub>2</sub><sup>-</sup> levels measured in mid-June of 2008 coincided with peak N<sub>2</sub>O emissions and low WFPS (Fig. 1–2). It is not clear if elevated DOC would enhance nitrification-driven N<sub>2</sub>O production (Venterea, 2007).

### Flux-Calculation Method

While it is well known that linear regression yields lower flux estimates than nonlinear schemes (Venterea and Baker, 2008), there have been few (if any) quantitative comparisons of seasonal-scale time-integrated N<sub>2</sub>O emissions based on differing schemes. To our knowledge this is also the first study to apply corrections for chamber-induced errors to seasonal data sets. Using theoretically simulated chamber data, Venterea et al. (2009) demonstrated inherent tradeoffs in selection of a flux-calculation scheme, i.e., while nonlinear schemes generated more accurate estimates, linear regression had greater precision. The current results are partly consistent with Venterea et al. (2009) in that CVs were generally higher with the quadratic model (Table 3). The CVs resulting from errors in applying flux-calculation schemes to chamber data will increase with decreasing flux and with increasing random error associated with sampling and analytical methods. In addition to these factors, the CV values in Table 3 also reflect actual variability in individual flux measurements during the course of two or three growing seasons. In contrast to the suggestions by Venterea et al. (2009), data generated by the linear model in this study were not more statistically robust than data generated from the quadratic model in that very similar *P* values and patterns of treatment differences were obtained by ANOVA using fluxes calculated from either the linear or nonlinear scheme.

### CONCLUSIONS

Based on measurements made during three consecutive seasons, this study found no evidence that differences in crop residue inputs from the previous growing season (i.e., corn vs. soybean) affected N<sub>2</sub>O emissions during the subsequent growing season in corn fertilized with either AA or U. In both C/C and C/S systems, however, N<sub>2</sub>O emissions from corn fertilized with AA were twice the emissions with U fertilization. After accounting for N<sub>2</sub>O emissions during the soybean phase,

it was estimated that a shift from C/S to C/C would result in an increase in emissions of 0.78 kg N<sub>2</sub>O-N ha<sup>-1</sup> (equivalent to 0.11 Mg CO<sub>2</sub>-C ha<sup>-1</sup>) with AA compared with an increase of only 0.21 kg N<sub>2</sub>O-N ha<sup>-1</sup> (0.03 Mg CO<sub>2</sub>-C ha<sup>-1</sup>) with U. In light of trends toward the use of less AA and more U (Glibert et al., 2006), these results suggest that fertilizer-induced N<sub>2</sub>O emissions may decline in the future, at least per unit of applied N. More studies are needed to systematically examine the effect of fertilizer form on N<sub>2</sub>O emissions in different soils and cropping systems. Also, a complete GHG life cycle analysis would need to account for the lower energy requirements associated with the manufacture and transport of AA compared with U (Snyder et al., 2007). Nitrous oxide and GHG assessments and models may be greatly improved if they can be adapted to account for the effects of fertilizer form.

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### REFERENCES

- Bremner, J., G. Breitenbeck, and A. Blackmer. 1981. Effect of anhydrous ammonia fertilization on emissions of nitrous oxide from soils. *J. Environ. Qual.* 10:77–80.
- Burford, J.R., and J.M. Bremner. 1975. Relationships between denitrification capacities of soils and total, water-soluble and readily decomposable soil organic matter. *Soil Biol. Biochem.* 7:389–394.
- Burgess, M.S., G.R. Mehuys, and C.A. Madramootoo. 2002. Nitrogen dynamics of decomposing corn residue components under three tillage systems. *Soil Sci. Soc. Am. J.* 66:1350–1358.
- Burton, D.L., X. Li, and C.A. Grant. 2008. Influence of fertilizer nitrogen source and management practice on N<sub>2</sub>O emissions from two Black Chernozemic soils. *Can. J. Soil Sci.* 88:219–227.
- Clay, D.E., S.A. Clay, Z. Liu, and S.S. Harper. 1995. Leaching of dissolved organic carbon in soil following anhydrous ammonia application. *Biol. Fertil. Soils* 19:10–14.
- Crutzen, P.J., A.R. Mosier, K.A. Smith, and W. Winiwarter. 2008. N<sub>2</sub>O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.* 8:389–395.
- Dörsch, P., A. Palojärvi, and S. Mommertz. 2004. Overwinter greenhouse gas fluxes in two contrasting agricultural habitats. *Nutr. Cycling Agroecosyst.* 70:117–133.
- Drury, C.F., X.M. Yang, W.D. Reynolds, and N.B. McLaughlin. 2008. Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. *Can. J. Soil Sci.* 88:163–174.
- Economic Research Service. 2009. U.S. fertilizer use and price. Available at [www.ers.usda.gov/Data/FertilizerUse/](http://www.ers.usda.gov/Data/FertilizerUse/) (verified 8 Dec. 2009). USDA Econ. Res. Serv., Washington, DC.
- Forster, P., V. Ramaswamy, P. Artaxo, T. Bernsten, R. Betts, D.W. Fahey, et al. 2007. Changes in atmospheric constituents and in radiative forcing. p. 129–234. *In* S. Solomon et al. (ed.) *Climate change 2007: The physical science basis*. Cambridge Univ. Press, Cambridge, UK.
- Glibert, P.M., J. Harrison, C. Heil, and S. Seitzinger. 2006. Escalating worldwide use of urea— a global change contributing to coastal eutrophication. *Biogeochemistry* 77:441–463.
- Gomez, K.A., and A.A. Gomez. 1984. *Statistical procedures for agricultural research*. 2nd ed. John Wiley & Sons, New York.
- Minnesota Climatology Working Group. 2009. Minnesota location selector. Available at [climate.umn.edu/mapClim2007/MNlocApp.asp](http://climate.umn.edu/mapClim2007/MNlocApp.asp) (verified 9 Dec. 2009). Minnesota State Climatology Office, St. Paul.
- Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping

- systems in northeastern Colorado. *J. Environ. Qual.* 35:1584–1598.
- Mosier, A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. Van Cleemput. 1998. Closing the global N<sub>2</sub>O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. *Nutr. Cycling Agroecosyst.* 52:225–248.
- Mulvaney, R.L., S.A. Khan, and C.S. Mulvaney. 1997. Nitrogen fertilizers promote denitrification. *Biol. Fertil. Soils* 24:211–220.
- National Agricultural Statistics Service. 2009. Crops and plants. Available at [www.nass.usda.gov/QuickStats/indexbysubject.jsp?Pass\\_group=Crops+%26+Plants](http://www.nass.usda.gov/QuickStats/indexbysubject.jsp?Pass_group=Crops+%26+Plants) (verified 9 Dec. 2009). NASS, Washington, DC.
- Omonode, R.A., T.J. Vyn, D.R. Smith, P. Hegymegi, and A. Gal. 2007. Soil carbon dioxide and methane fluxes from long-term tillage systems in continuous corn and corn–soybean rotations. *Soil Tillage Res.* 95:182–195.
- Parkin, T.B. 2008. Effect of sampling frequency on estimates of cumulative nitrous oxide emissions. *J. Environ. Qual.* 37:1390–1395.
- SAS Institute. 2003. SAS system for Windows, release 9.1. SAS Inst., Cary, NC.
- Snyder, C.S., T.W. Bruulsema, and T.L. Jensen. 2007. Greenhouse gas emissions from cropping systems and the influence of fertilizer management: A literature review. *Int. Plant Nutr. Inst., Norcross, GA.*
- Stevens, R., and R. Laughlin. 1995. Nitrite transformations during soil extraction with potassium chloride. *Soil Sci. Soc. Am. J.* 59:933–938.
- Thornton, F., B. Bock, and D. Tyler. 1996. Soil emissions of nitric oxide and nitrous oxide from injected anhydrous ammonia and urea. *J. Environ. Qual.* 25:1378–1384.
- Toma, Y., and R. Hatano. 2007. Effect of crop residue C:N ratio on N<sub>2</sub>O emissions from Gray Lowland soil in Mikasa, Hokkaido, Japan. *Soil Sci. Plant Nutr.* 53:198–205.
- Venterea, R.T. 2010. Simplified method for quantifying theoretical underestimation of chamber-based trace gas fluxes. *J. Environ. Qual.* 39:126–135.
- Venterea, R.T. 2007. Nitrite-driven nitrous oxide production under aerobic soil conditions: Kinetics and biochemical controls. *Global Change Biol.* 13:1798–1809.
- Venterea, R.T., and J.M. Baker. 2008. Effects of soil physical nonuniformity on chamber-based gas flux estimates. *Soil Sci. Soc. Am. J.* 72:1410–1417.
- Venterea, R.T., J.M. Baker, M.S. Dolan, and K.A. Spokas. 2006. Soil carbon and nitrogen storage are greater under biennial tillage in a Minnesota corn–soybean rotation. *Soil Sci. Soc. Am. J.* 70:1752–1762.
- Venterea, R.T., M. Burger, and K.A. Spokas. 2005. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. *J. Environ. Qual.* 34:1467–1477.
- Venterea, R.T., and D.E. Rolston. 2000. Nitric and nitrous oxide emissions following fertilizer application to agricultural soil: Biotic and abiotic mechanisms and kinetics. *J. Geophys. Res. D: Atmos.* 105:15117–15129.
- Venterea, R.T., K.A. Spokas, and J.M. Baker. 2009. Accuracy and precision analysis of chamber-based nitrous oxide gas flux estimates. *Soil Sci. Soc. Am. J.* 73:1087–1093.
- Wagner, S.W., D.C. Reicosky, and R.S. Alessi. 1997. Regression models for calculating gas fluxes measured with a closed chamber. *Agron. J.* 89:279–284.
- Wagner-Riddle, C., A. Furon, N.L. McLaughlin, I. Lee, J. Barbeau, S. Jayasundara, G. Parkin, P. von Bertoldi, and J. Warland. 2007. Intensive measurement of nitrous oxide emissions from a corn–soybean–wheat rotation under two contrasting management systems over 5 years. *Global Change Biol.* 13:1722–1736.
- Wagner-Riddle, C., and G.W. Thurtell. 1998. Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. *Nutr. Cycling Agroecosyst.* 52:151–163.
- West, T., and W. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Sci. Soc. Am. J.* 66:1930–1946.
- Wilson, H.M., and M.M. Al-Kaisi. 2008. Crop rotation and nitrogen fertilization effect on soil CO<sub>2</sub> emissions in central Iowa. *Appl. Soil Ecol.* 39:264–270.
- Zsolnay, A. 2003. Dissolved organic matter: Artefacts, definitions, and functions. *Geoderma* 113:187–209.