Nitrous Oxide Emission from No-Till Irrigated Corn: Temporal Fluctuation and Wheel Traffic Effects

Daniel Ginting* and Bahman Eghball

ABSTRACT

Field experiments were conducted to determine optimal time during the day for \( \text{N}_2\text{O} \) flux determination and to evaluate the effects of wheel traffic and soil parameters on \( \text{N}_2\text{O} \) fluxes following urea ammonium nitrate (UAN) injection and summer UAN fertigations. The experiments were located on silty clay loam soils under no-till irrigated continuous corn of eastern Nebraska. Three approaches were used. First, near-continuous \( \text{N}_2\text{O} \) flux measurements were made in non-wheel-tracked (NWT) interrows in four 24-h periods during the growing season of 2002. Second, point measurements of \( \text{N}_2\text{O} \) flux were made in the wheel-tracked (WT) and NWT interrows at five dates during the growing season of 2002. Third, point measurements of \( \text{N}_2\text{O} \) fluxes and soils (nitrate, ammonium, moisture, and temperature) were made in the NWT interrows from 2001 to 2004. The differences between point vs. continuous flux measurements (\(<8 \text{ g N}_2\text{O-N ha}^{-1} \text{ d}^{-1}\)) and between the WT vs. the NWT (\(<3.7 \text{ g N}_2\text{O-N ha}^{-1} \text{ d}^{-1}\)) were not significant. The means of \( \text{N}_2\text{O} \) daily flux within 60 d after injection were made in the NWT interrows from 2001 to 2004. The differences between point vs. continuous flux measurements (\(<8 \text{ g N}_2\text{O-N ha}^{-1} \text{ d}^{-1}\)) and between the WT vs. the NWT (\(<3.7 \text{ g N}_2\text{O-N ha}^{-1} \text{ d}^{-1}\)) were not significant. The means during low soil N were 9.24, 4.05, and 7.50 g \( \text{N}_2\text{O-N} \) ha\(^{-1}\) d\(^{-1}\), respectively. The means during low soil N were 9.24, 4.05, and 7.50 g \( \text{N}_2\text{O-N} \) ha\(^{-1}\) d\(^{-1}\), respectively. Summer fertigations did not increase \( \text{N}_2\text{O} \) flux. Under the conditions of this study, optimal point measurement for \( \text{N}_2\text{O} \) daily flux can be made any time during the day at the NWT interrows. Among the soil parameters, soil nitrate dynamics in the injection zone correlates best with \( \text{N}_2\text{O} \) fluxes.

Nitrous oxide has negative impacts on the chemistry of earth stratosphere and also increases atmospheric radiative force. Increasing soil \( \text{N}_2\text{O} \) emission from N application has raised concern over \( \text{N}_2\text{O} \) emission to the atmosphere (Yanai et al., 2002) limit our ability to accurately estimate \( \text{N}_2\text{O} \) emission from agricultural land. Temporal and spatial variations of \( \text{N}_2\text{O} \) are usually the main sources of error in estimating \( \text{N}_2\text{O} \) emission (Flessa et al., 2002). To better capture the temporal variation, a continuous (or near-continuous) flux measurement technique has been developed. In the continuous technique, the daily flux is determined by measuring flux several times a day (24-h period) to represent the diurnal flux cycle. Usually the continuous technique requires electricity to power sophisticated controllers and online gas analyzers (Riddle et al., 1997; Magiotto et al., 2000; Flessa et al., 2002; Papen and Butterbach-Bahl, 1999). When the continuous technique is not practical, the point flux measurement technique is commonly used. In the point measurement technique, the daily flux is determined by measuring only one flux a day during the period of interest. Usually gas samples are collected from the field in prevacuumed vials and brought to the laboratory for analysis (Bremner et al., 1981; Lessard et al., 1996; Ginting et al., 2003). The main limitation of point flux measurements lies in the accuracy of the daily flux estimation due to the diurnal flux cycle.

In many cases, the periods of high fluxes (that would make the major part of annual emission) are unknown. Therefore, inadequate frequency of point measurements would result in an erroneous estimate of seasonal or annual emission. Various \( \text{N}_2\text{O} \) point sampling frequencies have been reported in the literature, on average one per week or one per 2 to 3 wk (Teepe et al., 2004), and in rare cases one per month (Ambus and Christensen, 1995). There was no clear reason stated by the authors as to how these sampling frequencies were determined. Using a near-continuous technique on a ridge-tilled potato field, Flessa et al. (2002) concluded that weekly point \( \text{N}_2\text{O} \) flux measurements resulted in excellent estimation of cumulative fluxes when complemented with event-related (after rain and harvest) flux measurements. The authors further concluded that monthly sampling was not adequate to capture temporal variation of \( \text{N}_2\text{O} \) emission.

In addition to the diurnal and seasonal \( \text{N}_2\text{O} \) fluctuation, flux may also vary spatially due to machinery wheel traffic on tilled soil (Hansen et al., 1993; Ruser et al., 1998; Flessa et al., 2002). Flessa et al. (2002) associated high \( \text{N}_2\text{O} \) emission with interaction of machinery-related soil compaction and heavy precipitation. While machinery-related compaction studies have been conducted in tilled soil, there has been no \( \text{N}_2\text{O} \) study on irrigated no-till continuous corn, where N fertilizer is commonly applied by injection and/or fertigations. In no till corn systems, soil bulk density is commonly high due to consolidation (Canqui et al., 2004; Wander and Bollero, 1999), yet soil biological activity is also high (Logsdon and Cambardella, 2000).

For practical reasons, repetitive \( \text{N}_2\text{O} \) measurement during a year should be made in an interrow other than the power unit WT interrow (e.g., tractor or combine dual wheel tracks) because removing and reinstalling experimental equipment in the power unit wheel-track interrow for every field operation would be laborious and may affect the consistency and accuracy of \( \text{N}_2\text{O} \) measurement. The difference between the WT and NWT interrows in \( \text{N}_2\text{O} \) emission from no-till corn is unknown.

Abbreviations: NWT, non-wheel-tracked; UAN, urea ammonium nitrate; WFP, water filled porosity; WT, wheel-tracked.
There is a need for information to help in deciding when and where the measurements of N$_2$O flux and the corresponding soil properties should be made to capture the dynamics of N$_2$O fluctuation under a no-till irrigated continuous corn system, where N fertilizer is usually applied by injection and fertigation. To the best of our knowledge, there has been no study focusing on the temporal (diurnal and seasonal) variation and wheel traffic effects on N$_2$O fluxes in this type of no-till system. The appropriate hour for a representative daily flux measurement (representing diurnal cycle of fluxes) and the appropriate frequency of point measurements (capturing the period of high and low fluxes in a year cycle from a UAN injection to the next year UAN injection) are not known.

The objectives of this experiment were (i) to determine representative times for point measurements of daily flux that represent N$_2$O diurnal fluctuation, (ii) to evaluate wheel traffic effects on N$_2$O flux, and (iii) to evaluate the interrelation of soil properties and N$_2$O fluxes following UAN injection and UAN fertigation in a no-till irrigated continuous corn system.

**MATERIALS AND METHODS**

**Site Description and Field Operations**

This experiment is part of a multidiscipline soil carbon sequestration project. The carbon sequestration project at the Agricultural and Research Development Center, near Mead, NE (41°6′ N, 96°30′ W, 366 m above sea level), has been running since May 2001. Information about various projects in this multidiscipline study is available at [http://csp.unl.edu/](http://csp.unl.edu/) public (verified 28 Jan. 2005).

Six plots (20 by 20 m) were selected from a 45-ha land under a center pivot irrigation system. The soils are deep silty clay loams consisting of four soil series: Yutan (fine-silty, mixed, superactive, mesic Mollic Hapludalfs), Tomek (fine, smectitic, mesic Pachic Argiudolls), Filbert (fine, smectitic, mesic Vertic Argiudolls), and Fillmore (fine, smectitic, mesic Vertic Argiudolls). Each plot represented distinct properties classified based on fuzzy-$k$-means cluster analysis (Minasny and McBratney, 2002). Fuzzy classification used direct measurements of soil organic matter content (0- to 0.2-m depth at 2 samples ha$^{-1}$), soil EC, and topographical relative elevation. Indirect measurements in the fuzzy cluster analysis included a digital orthophoto of bare soil in the spring of 1993, soil map, and near-infrared map of the May-2000 IKONOS image of the area. The description of the six plots (fuzzy classes) numbered from 1 to 6 is presented in Fig. 1.

During the 10 yr before initiation of the study in 2001, the area had been in an irrigated no-till corn–soybean cropping sequence. The area was chisel plowed in spring 2001 to create uniform initial conditions and has been under no-till continuous corn since then. Soil disturbance occurred only during spring UAN injection and corn planting. After planting in 2001 and before planting in 2002 and 2003, UAN was injected at the 7.5-cm depth, 15 cm away from the corn rows with knife implements at the rate of 144 kg N ha$^{-1}$. Corn was planted at 41 000 seed ha$^{-1}$ on the previous corn rows using a no-till planter. During growing season, irrigation was applied with a center pivot system that was automatically turned on when soil moisture decreased to 70% field capacity. In the summer, UAN was applied twice via irrigation water at a rate of 36 kg N ha$^{-1}$ for each fertigation in 2001 and 48 kg N ha$^{-1}$ in 2002 and 2003. Corn residue was left in the field after harvest, which occurred during the months of October or November every year. Dates of major field operations are presented in Table 1.

The same wheel traffic paths were used during the experiment. The WT interrow was the interrow beneath the tractor inner dual-wheel (Fig. 2B). Every year, multiple passes of trac-
tor wheels occurred in the WT interrow for spring UAN injection, planting, and harvesting. The NWT interrow was the interrow beneath the planter gauge and drive wheel (Fig. 2B), which gauges the planter frame and drives the seed metering. The planter gauge and drive wheels, smaller and lighter compared with tractor dual wheels, passed through the NWT interrow once a year during planting. Both the WT and NWT interrow received the same rate of UAN application as previously described.

Gas Sampling Protocol

Our vented chamber was similar in principle to the vented chamber of Hutchinson and Mosier (1981). Our vented chamber had two parts, chamber base and chamber cap. The chamber base was an aluminum ring (69-cm i.d., 7.5-cm height). The base was inserted 3 to 4 cm into the weed-free soil between two cornrows (76-cm spacing, Fig. 2A) and functioned as a stationary sampling location. The length of the UAN band enclosed within the circular chamber was 51.4 cm, 2.8 cm (5.1%) shorter compared with the length of UAN band (54.2 cm)

### Table 1. Dates of major field operations at the no-till irrigated continuous corn field in eastern Nebraska.

<table>
<thead>
<tr>
<th>Activities</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring disking</td>
<td>18 Apr.</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Field cultivation</td>
<td>9 May</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>UAN injection</td>
<td>10 May</td>
<td>16 Apr.</td>
<td>14 Apr.</td>
</tr>
<tr>
<td>Corn planting</td>
<td>9 May</td>
<td>9 May</td>
<td>15 May</td>
</tr>
<tr>
<td>UAN fertigation†</td>
<td>18 June</td>
<td>17 June</td>
<td>23 June</td>
</tr>
<tr>
<td>Harvest</td>
<td>18 Oct.</td>
<td>4 Nov.</td>
<td>27 Oct.</td>
</tr>
</tbody>
</table>

† UAN, urea ammonium nitrate. 

The chamber cap was an aluminum ring similar to the chamber base (21-cm height) welded to a vented lid. The vent was a 2-mm-diam. opening of a 32-cm long copper tube suspended horizontally under the lid. Four sampling tubes (1-mm i.d.) were inserted through a septum on the center of lid and lowered vertically to 10 cm underneath the lid. An electric motor

![Fig. 2. (A) Schema of circular chamber location relative to urea ammonium nitrate (UAN) injection zone, and (B) tractor-wheel-tracked and non-wheel-tracked interrows.](image)

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with a 10-cm fan was secured to the chamber wall inside the chamber cap, 10 cm underneath the lid. 20 cm from the sampling tube. An O-shape rubber sleeve (5-cm width) taped to the lower portion of the chamber cap functioned as a coupling to seal the joint between the chamber cap and the chamber base. Our laboratory test indicated that gas exchange (measured by the change of known gas concentration inside the chamber during a period of time) through the seal and the copper tube within 45 min was undetectable.

Gas samples were collected with a 30-mL syringe via the sampling tubes at 0, 5, 10, and 15 min after sealing the chamber; each sampling time corresponded to each sampling tube. Before each sampling, a controller turned on the fan for 30 s to mix the air in horizontal direction within the chamber. Mixing air in a horizontal direction for a short pulse was intended to minimize disturbance of gas transmission from the soil enclosed by the chamber. Using the syringe, 20 mL of gas was transferred into 12-mL evacuated serum vials and transported to the laboratory. The N2O-N concentrations were determined with an automated gas chromatographic system using a Poropak Q (Waters Associates, Farmington, MA) column and electron capture detector as described by Arnold et al. (2001). Gas flux was calculated as the difference of gas concentrations multiplied by chamber volume per unit area covered by the chamber per unit time, as described in detail by Ginting et al. (2003). At each air sampling, soil temperature was measured outside the chamber at the 7.5-cm depth, 25 cm from the chamber.

Point Sampling Time Representing Diurnal Gas Fluxes

To mimic continuous flux measurement technique, frequent point measurements of N2O fluxes within a 24-h period were made in the NWT interrows of Plots 4, 5, and 6 (the three north plots in Fig. 1) on 6 and 20 June, and 2 and 24 July 2002. These dates were selected to include periods of different stages of corn growth from 10% canopy cover (6 June) to full canopy closer (24 July). For each plot, N2O flux measurements were made every 4 h within a 24-h period (i.e., at 0800, 1200, 1600, 2000, and 2400 h, and 0400 and 0800 h the next day). The daily flux (g N2O-N ha⁻¹ d⁻¹) for each 24-h period was calculated as:

\[
\text{continuous daily flux} = 4 \sum_{i=1}^{6} \left( F_i + F_{i+1} \right) \frac{1}{2}
\]  

The point estimate of the daily flux (g N2O-N ha⁻¹ d⁻¹) for each sampling time in each 24-h period was calculated as:

\[
\text{ith point daily flux} = 24 \times F_i
\]

In Eq. [1] and [2], the variables \( F_i \) and \( F_{i+1} \) were the flux (g N2O-N ha⁻¹ h⁻¹) measured at 0800 h, 1200 h, 1600 h, 2000 h, and 2400 h, and 0400 h, 0800 h the next day, respectively.

For each 24-h period, the experiment was a randomized complete block design. The blocks were the three plots representing three distinct fuzzy classes. The continuous daily flux (as a control) and the seven-point daily flux (seven sampling times) were regarded as treatments. Flux pair comparisons between the control vs. the treatments were made using the Dunnett test of the General Linear Model Procedure (SAS, 1992) at \( \alpha = 0.1 \).

If the difference between a treatment and the control was not significant, it was inferred that there was not enough evidence to declare that the daily flux determined with the point measurement technique was different from the daily flux determined with continuous measurement technique; thus, the point daily flux was a representative estimate of the continuous daily flux. If there was consistent evidence that the point daily fluxes of two or more consecutive sampling times were not different from the control, then it was likely that a point daily flux measured at any time within the period of the two or more consecutive sampling times (e.g., from 0800 h to 1200 h, from 1200 h to 0400 h, or from 0800 h to 1600 h) was also not different from the continuous daily flux.

Wheel Traffic Effects on N2O Fluxes

One interrow representing a tractor-wheel-tracked condition and one adjacent interrow representing a NWT condition were selected. The row direction was parallel to the toposequence, 10 m from Plots 4, 5, and 6 (Fig. 1). Within the WT and NWT interrows, six locations were selected for gas flux measurements. The six locations were at distance 0 m (toe slope), 46 m (toe slope), 74 m (foot slope), 101 m (foot slope), 136 m (back slope), and 179 m (summit). Elevation difference between the summit and the toe slope was 3 m.

Point daily flux measurements were made on five dates: 22 May, 6 June, 2 and 17 July, and 14 Aug. 2002. Flux measurements were made from 0900 h to 1130 h. At each date, a composite sample from three soil cores (0- to 20-cm depth) was obtained from the same interrow where the chamber was placed. The soil cores were collected with soil probes (1.8 cm i.d.) 1 m from the chamber. One soil core was collected 0.15 m from one corn row (at the UAN injection zone), one 0.15 m away from the next corn row, and one from the center of the interrow. The three soil samples were mixed and stored in a sealed plastic bag for moisture and bulk density measurements.

For each sampling date, the experiment was a randomized complete block design. The six sampling positions were the blocks and the WT and NWT interrows were the treatments. Measurements along the toposequence were intended to separate the effects of topography on N2O fluxes in the ANOVA. The ANOVA and means comparison were made using the general linear model procedure (SAS, 1992) at \( \alpha = 0.1 \).

Seasonal Flux Fluctuation

From April 2001 to April 2004, point daily flux measurements were made in the six plots. In each plot, point measurement was made in the NWT interrow at 1, 3, and 10 d after UAN injection followed by flux measurements every 1 to 2 wk from May to July, every other week from August to October, and once a month from November to April. More frequent measurements were made in the first 60 d after UAN injection (May to July) because N2O fluxes were expected to be higher relative to the rest of the year. On the basis of previous studies, depending on N source, the majority of N2O emission occurred within 10 d after N application (Leick and Engels, 2001; Lessard et al., 1996) or from 15 to 42 d after N application (Bremner et al., 1981). From each plot at each date of air sampling, a composite of three soil cores (0–20 cm depth) was obtained from the same interrow where the chamber was placed. Soil sampling was made in the same manner as described in the previous section describing the wheel traffic effects. Soil samples were analyzed for bulk density, moisture, nitrate, and ammonium.

Since N2O-N production likely occurred at the narrow band of UAN injection (15 cm away from corn rows), two other soil samples were collected during the growing season in 2003. The two soil samples (20-cm depth) were taken 0.0 and 0.23 m from the UAN injection band. Each sample was a combination of three soil cores. The soil samples were brought to the laboratory, air dried, ground to pass a 2-mm opening, and analyzed for nitrate and ammonium. These data were used to
determine the dynamics of soil nitrate and ammonium across time at the UAN injection point and at 0.25 m away from the injection.

Soil nitrate and ammonium concentrations and N₂O flux before each UAN injection were regarded as background soil N concentrations and N₂O flux for each year. Soil nitrate and ammonium concentrations were high in the injection zone within 60 d after injection and were similar to background level beyond 60 d after injection. Fluxes were separated based on the periods of high soil N and the period of low soil N. To compare the differences between the two periods in a yearly-cycle of UAN injection, the experiment was a randomized complete block design with repeated measures. In this case, the blocks are the six plots that represented the six distinct fuzzy classes, the two periods were treatments, and the numbers of sampling dates within each N level were repeated measures. Analysis of variance and means comparison were made using the General Linear Model Procedure (SAS, 1992) at α = 0.1.

### RESULTS AND DISCUSSION

#### Diurnal Flux Fluctuation

Among the ancillary measurements, diurnal fluctuations were observed only for soil temperature. Soil temperature diurnal pattern occurred only at the early stages of corn growth in June samplings (Fig. 3A and 3B), when corn canopy cover provided little interception of solar radiation. When corn provided a complete canopy cover, for example, on 2 and 24 July, no diurnal cycle of soil temperature could be detected within the 24-h period (Fig. 3C and 3D). No diurnal pattern of N₂O flux was observed at any of the four sampling dates. Failure of N₂O flux to follow diurnal soil temperature indicated that soil temperature was not a limiting factor in making a decision regarding the timing of point N₂O sampling in a 24-h period during the growing season.

![Diurnal pattern of N₂O fluxes at various 24-h cycles during corn growing season in 2002. Vertical bars on the soil temperature are the standard error of the means (n = 3) and Dunnett’s LSD is for differences between point and continuous daily flux.](image)

**Fig. 3.** Diurnal pattern of N₂O fluxes at various 24-h cycles during corn growing season in 2002. Vertical bars on the soil temperature are the standard error of the means (n = 3) and Dunnett’s LSD is for differences between point and continuous daily flux.
Lack of agreement between diurnal pattern of soil temperature and N₂O flux was also observed by Blackmer et al. (1982) in an experiment where temperature was measured at the 2 cm depth and urea was applied. On a fertilized fallow soil, Blackmer et al. (1982) observed that the phase of N₂O emission lagged or was the inverse of soil temperature diurnal pattern. According to Lessard et al. (1996), lack of agreement between soil temperature and N₂O flux at the soil surface indicated that N₂O flux was diffusion driven as opposed to soil temperature driven. Our data and Blackmer et al. (1982) disagreed with those of DenMead et al. (1979) who observed a similar phase between N₂O and soil temperature diurnal fluctuations. We presume that the difference between our result and those of DenMead et al. (1979) was due to soil differences. We made N₂O measurements on weed-free soil as opposed to a grass sward in the experiment by DenMead et al. (1979). Rapid response of grass mixture on the sward to soil temperature might have caused the rapid response of N₂O emission to the soil temperature.

Statistical analysis indicated that the estimated daily fluxes based on point measurements were not statistically different from the daily fluxes based on continuous measurements. The plots (fuzzy classes) had little effects on N₂O flux. Therefore, a flux point measurement at any time during the day can be considered representative of the daily flux. Sherlock et al. (2002) specified N₂O point measurement at 1200 h to represent a daily flux, although the authors based the 1200 h sampling time only on two point measurements (1000 and 1600 h), representing only a portion of daylight time and not nighttime.

Our result provides a wide sampling window for manual N₂O measurements during daylight time. The wide sampling window for N₂O measurement suggests a precaution in simultaneous multiple gas (CO₂ and N₂O) measurement. Air sampling from 0800 to 1000 h that is representative for CO₂ daily flux (Parkin and Caspar, 2003) will also be representative for N₂O daily flux. However, point sampling time from 1200 to 1600 h that is representative for N₂O daily flux will be unrepresentative for CO₂ daily flux because CO₂ flux is greatly dependent on soil temperature nearing maximum at 1200 or 1600 h before canopy closer.

### Wheel Traffic Effect on N₂O Flux

Wheel traffic had no significant effect on a specific soil physical property [bulk density, soil moisture, and water filled porosity (WFP)] and N₂O fluxes. Soil bulk density in the WT (1.40 Mg m⁻³) and NWT (1.34 Mg m⁻³) interrows were not statistically different at the 0.1 probability level. Lack of difference in bulk density could be due to freeze and thaw cycles. Unger (1991) observed that the reduction of bulk density from 1.37 to 1.27 Mg m⁻³ in the first overwinter of a reduced tillage system was at the 4- to 7-cm depth. Previous study by Lindstrom et al. (1981) also found no statistical difference between WT (1.41 Mg m⁻³) and NWT (1.35 Mg m⁻³) interrows under no till system in Minnesota. In our case, the depth of soil bulk density measurements (20 cm) might also have obscured the bulk density difference. Small depth increments might detect bulk density differences that would be obscured in a large depth increment samples. Lack of difference in soil bulk density could also be due to soil biological processes. Logsdon and Cambardella (2000) indicated that differences in no-till bulk density at the 0- to 12-cm depth was partially due to biopores from surface-feeding earthworms (Lumbricus terrestris L.) that were observed in the no-till field but not in the disk field.

There was not enough evidence to suggest that N₂O flux was different between the WT and NWT interrows (Table 2). Using sampling locations along the toposequence as blocking variable in the ANOVA had little effect on the precision of the comparison between the WT and NWT interrows. This implied that under the conditions of our study, the effect of topography on N₂O fluxes was not significant. Another factor that might obscure the effects of wheel track on N₂O flux was the soil disturbance by injector knife. The applicator knife opened a 7.5-cm-deep slot and the liquid UAN was forced into the slot from a hose behind the knife. The injection zone, therefore, was a narrow band of loosened soil with high concentration of nitrate and ammonium. Even if there had been differences in stratifications of bulk density due to soil compaction in most portions of the WT the NWT interrows, differences in N₂O fluxes between the two interrows might not be detectable because, as discussed in the next section, the main source of N₂O was the high-N injection zone.

### Fluctuation Patterns of Gas Flux and Soil Processes

#### Annual Pattern of N₂O Flux Fluctuation

The N₂O flux did not increase above the background level within 13 d after UAN injection (Fig. 4C and repeated in Fig. 6C). In Year 1, fluxes were above the background level within 13 to 44 d after injection. The fluxes decreased to the background level beyond 51 d after injection. This pattern was clearer in Year-Cycles 2 and 3. In Year 2, N₂O fluxes peaked at 13 and 41 d after injection. In Year 3, N₂O fluxes peaked at 16 and 44 d after injection. In general, the fluxes decreased to the background level beyond 60 d after UAN injection.

In all years, UAN fertigations (at 39 and 53 d after injection in Year1, at 62 and 77 d after injection in Year 2, and at 71 and 87 d after injection in Year 3) did not result in elevated N₂O emission. Application of 48 kg UAN-N ha⁻¹ in each of two fertigations (in many ways similar to broadcasting) when crop N requirement was high resulted in negligible emission compared with one-time spring UAN injection before corn planting. This in-

<table>
<thead>
<tr>
<th>Date</th>
<th>WT</th>
<th>NWT</th>
<th>LSD</th>
<th>F</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 May</td>
<td>4.23</td>
<td>6.06</td>
<td>6.65</td>
<td>0.31</td>
<td>0.603</td>
</tr>
<tr>
<td>6 June</td>
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<td>3.07</td>
<td>7.77</td>
<td>0.01</td>
<td>0.929</td>
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<tr>
<td>2 July</td>
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<td>2.91</td>
<td>7.13</td>
<td>0.00</td>
<td>0.960</td>
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<tr>
<td>17 July</td>
<td>11.40</td>
<td>9.69</td>
<td>4.26</td>
<td>0.61</td>
<td>0.469</td>
</tr>
<tr>
<td>14 August</td>
<td>4.49</td>
<td>0.76</td>
<td>6.94</td>
<td>1.17</td>
<td>0.328</td>
</tr>
</tbody>
</table>
Fig. 4. Fluctuation of soil water filled porosity (WFP), soil temperature, and N₂O flux for each yearly cycle of urea ammonium nitrate (UAN) injection under a no-till irrigated continuous corn. Vertical bars are standard errors of the means (n = 6) at each sampling day.

Pattern of Soil Moisture and Temperature

Precipitation plus irrigation resulted in relatively stable soil moisture within 0.2 to 0.3 g g⁻¹ each year, which was equal to WFP within 0.50 to 0.98 (Fig. 4A). When N₂O fluxes were elevated, within 60 d after injection, the WFP varied from 0.50 to 0.85. For the rest of the year, when N₂O fluxes were similar to the background level, the WFP varied from 0.42 to 0.98 (Fig. 4C). The high or low N₂O fluxes occurred for the wide range of WFP, which implied that there was little agreement in patterns between N₂O flux and soil WFP. In our study, the correlation coefficients were <0.21. Lack of agreement between N₂O fluctuation and WFP was also observed by previous studies, where the correlation coefficients were <0.31 in a no-till corn system (Thornton et al., 1996) and <0.48 in a pasture system (Barton and Schipper, 2001).

Soil temperature increased rapidly within 60 d after UAN injection (Fig. 4B) when elevated N₂O fluxes occurred (Fig. 4C). Soil temperature reached its high (during 60 to 130 d after injection) and low (during 190–330 d after injection) (Fig. 4B). There was little agreement in patterns between soil temperature and N₂O flux (Fig. 4C). Peaks of N₂O flux did not correspond to peaks in soil temperature. The N₂O flux decreased to a background level beyond 60 d after injection when soil temperature increased and the period of elevated emission lasted for about 60 d.

Pattern of Soil Nitrate and Ammonium

Dynamics and initially high concentrations of soil ammonium and nitrate at the 0- to 20-cm depth occurred only in the UAN injection zone (Fig. 5A and 5B). Nitrate and ammonium concentration 0.23 m away from...
the injection zone had little fluctuation across the year and failed to indicate the high fluctuation of $N_2O$ flux within 60 d after UAN injection (Fig. 5D). Obscuring soil $N$ dynamics due to sample compositing is shown in Fig. 6A and 6B. Soil ammonium and nitrate was $<30$ mg N kg$^{-1}$ most of the time. Our data suggests that when $N$ fertilizer was applied by injection, soil $N$ data from composite samples intended for cropping purposes should not be used in describing $N_2O$ dynamics.

Soil ammonium decreased from 202 to 90 mg N kg$^{-1}$
16 d after injection, and increased again to 159 mg N kg\(^{-1}\) 24 d after injection. Soil ammonium decreased rapidly to 19 mg N kg\(^{-1}\) 30 d after injection and decreased further to 4.5 mg N kg\(^{-1}\) at 51 d after injection. For the rest of the year (beyond 52 d after injection) soil ammonium in the injection zone was similar to the ammonium 0.23 cm from the injection zone (Fig. 5B).

Soil nitrate concentration (80 mg N kg\(^{-1}\) at 2 d after injection) decreased to 27 mg N kg\(^{-1}\) 16 d after injection. The decrease in ammonium and nitrate was followed by an increase in N\(_2\)O flux, which peaked 16 d after UAN injection (Fig. 5C). Within the period from 16 to 30 d after injection, little change in soil nitrate concentration (thus little production of N\(_2\)O) decreased N\(_2\)O fluxes to the background level 30 d after injection. As soil nitrate increased due to nitrification from 31 (30 d after injection) to 50 mg N kg\(^{-1}\) (37 d after injection) N\(_2\)O flux increased and peaked 44 d after injection. Our data showed that the decrease (due to nitrification) or the increase (due to nitrification) in soil nitrate in the injection zone resulted in increasing N\(_2\)O fluxes. This further supports the facts that N\(_2\)O was produced both during nitrification and denitrification processes. For the rest of the year (beyond 52 d after injection), when soil ammonium and nitrate in the injection zone was low, soil N\(_2\)O flux fluctuated less and was similar to N\(_2\)O flux before UAN injection.

It appeared that the fluctuation pattern of N\(_2\)O flux was governed by soil N, especially nitrate N at the UAN injection zone. Accounting for the 16-d lag between UAN injection and the first flux peak in 2003 (Fig. 5), the correlation coefficient between N\(_2\)O flux and soil nitrate, ammonium, and soil N was 0.79, 0.70, and 0.76, respectively. Stepwise multiple regression analysis resulted in nitrate as the only significant variable explaining 62% of N\(_2\)O flux variability. Similar observation was reported by Thorton et al. (1996), indicating high correlation coefficient of 0.74 between nitrate concentration in the fertilizer band and N\(_2\)O flux.

The means of N\(_2\)O emission were much higher for the period within 60 d after injection (period of high soil N) vs. the period beyond 60 d after injection (period of low soil N). Since N\(_2\)O fluxes and their fluctuation were much greater during the period of high soil N and low soil N. Since N\(_2\)O fluxes and their fluctuation were much greater during the period of high soil N than the period of low soil N, efforts on N\(_2\)O flux measurements should be emphasized more on the high soil N period within 60 d after UAN injection.

### Table 3. Means comparison of daily N\(_2\)O fluxes within 60 d after injection (the period of high soil N) vs. fluxes beyond 60 d after injection (the period of low soil N).

<table>
<thead>
<tr>
<th>Year cycle</th>
<th>Within 60 d after injection</th>
<th>Beyond 60 d after injection</th>
<th>LSD (_{a=0.05})</th>
<th>F</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2001–April 2002</td>
<td>26.8</td>
<td>9.24</td>
<td>12.4</td>
<td>7.88</td>
<td>0.038</td>
</tr>
<tr>
<td>April 2002–April 2003</td>
<td>21.2</td>
<td>4.05</td>
<td>10.0</td>
<td>11.96</td>
<td>0.018</td>
</tr>
<tr>
<td>April 2003–April 2004</td>
<td>28.0</td>
<td>7.50</td>
<td>11.0</td>
<td>15.23</td>
<td>0.011</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

We observed no clear diurnal pattern of N\(_2\)O fluxes occurred even when soil temperature had a diurnal pattern. The method of UAN injection resulted in similar N\(_2\)O flux between the WT and the NWT interrows. Sampling for N\(_2\)O in the NWT interrows represented the WT interrows; thus, under the condition of this study, there was no need to sample WT interrows. Nitrous oxide flux and its fluctuation were much higher in the period of high soil N (within 60 d after injection) than in the period of low soil N in the UAN injection zone. Soil nitrate and ammonium measured at 0.23 m away from the UAN injection zone or composite samples across the interrow did not relate well to N\(_2\)O flux. This study concludes that following UAN injection in the growing season of a no-till irrigated-corn system, point measurements of N\(_2\)O daily flux can be made any time during the day at the NWT interrow. Among the soil parameters, soil nitrate dynamics in the injection zone correlates best with N\(_2\)O fluxes.

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### REFERENCES


