Soil Denitrification and Nitrous Oxide Losses under Corn Irrigated with High-Nitrate Groundwater

Jin H. Qian, John W. Doran,* Keith L. Weier, Arvin R. Mosier, Todd A. Peterson, and James F. Power

ABSTRACT

Inappropriate management of irrigation water and fertilizer N in irrigated corn (Zea mays L.) has resulted in excess N leaching from the rooting zone and NO₃⁻ contamination of groundwater. A better understanding of microbially mediated conversion of plant available N to gaseous N forms is needed for more efficient N use, to evaluate the impact of radiatively important gas production such as nitrous oxide (N₂O) on air quality, and to determine the potential of microbial denitrification for remediating high-NO₃⁻ irrigation water. Soil denitrification and N₂O losses from pivot irrigated corn were measured during the 1991 and 1992 growing seasons using surface gas chambers at the Management System Evaluation Area (MSEA) site for water quality research in the Central Platte Valley near Shelton, NE. Denitrification and N₂O losses remained low throughout most of the growing season, generally ranging from 10 to 50 g N ha⁻¹ d⁻¹, when soil water contents were generally below 60% water-filled pore space (WFPS). Nitrous oxide was the major gaseous N product under these conditions. When soils were wetted by irrigation or rainfall to >70% WFPS, denitrification losses ranged from 0.2 to 1.4 kg N ha⁻¹ d⁻¹ with N₂ comprising 80 to 98% of the denitrification gases measured. Monthly average denitrification losses across years were highly correlated (r = 0.693) with time of growing season, suggesting a possible link between plant growth and denitrification. Seasonal gaseous N losses via denitrification and N₂O emission from irrigated corn represented 1 to 5% of the N applied as fertilizer or in irrigation water during a relatively dry 1991 season and the 1992 season with near normal precipitation. Results of our 2-yr study indicate that under good irrigation and N management practices gaseous N losses from denitrification and N₂O production pose little additional threat to atmospheric quality or N-use efficiency but also provide little hope for bioremediation of high-NO₃⁻ groundwater.

ECONOMIC CONSTRAINTS and concern for environmental quality during the final decade of this century challenge producers and researchers to develop agricultural production systems that use resources more efficiently and reduce nutrient losses to the environment. Efficient use of N fertilizer for grain crop production in irrigated agriculture is often limited by a lack of synchrony between microbial release of available N from soil organic matter and seasonal uptake needs by grain crops. Fertilizer N applied in excess during early season corrects this problem, but can result in NO₃⁻ movement below the root zone and eventual NO₃⁻ contamination of groundwater (Olson et al., 1970; Spalding and Kitchen, 1988) or in gaseous loss of N to the atmosphere through microbial denitrification and N₂O emission (Hauck, 1981; Aulakh, et al., 1992).

Nitrous oxide is produced by microorganisms during the O₂-requiring nitrification of NH₄⁺ to NO₃⁻ and during denitrification, a process that occurs in soils with limited O₂ availability, in which NO₃⁻ is reduced stepwise to NO₂⁻, NO, N₂O, and N₂ (Firestone, 1982; Aulakh, et al., 1992). Denitrification is an important component of N cycling in soils of most terrestrial ecosystems and usually is one of the major mechanisms for gaseous N loss from soil. Denitrification losses are generally quantified in the field by estimating the end-products N₂O and N₂ in the soil, air, or at the soil surface. Lysimeter and ¹⁵N studies indicate that, depending on crop and climate, from 12 to 20% of added fertilizer N is unaccounted for and presumed lost via denitrification (Hauck, 1981). This variability is undoubtedly a function of the various environmental factors that control its rate in soil, such as available C, water content, NO₃⁻ concentration, O₂ availability, pH, and temperature (Firestone, 1982; Tiedje, 1988; Aulakh et al., 1992).

The N₂O produced during nitrification and denitrification contributes to global warming and stratospheric ozone depletion. The total amount of N₂O emitted globally from N-fertilized soils is estimated to be 1.5 Tg N₂O-N yr⁻¹ (Seiler and Conrad, 1987), which represents about 10% of the total annual global N₂O-N emissions to the atmosphere (IPCC, 1995). However, the magnitude of N₂O production varies greatly, both among and within ecosystems. Minimizing denitrification and gaseous emissions of N₂O in cropping systems is therefore an important economic as well as an environmental concern. Better understanding of N cycling processes in irrigated cropping systems, particularly the microbial conversion of plant available N to gaseous N forms is needed for most efficient use of soil and fertilizer N, for evaluation of agricultural management effects on air quality, for determining the potential of microbial denitrification for remediating high-NO₃⁻ irrigation water and groundwater contamination, and for aiding in the selection of best N management practices for sustainable agriculture. The objectives of our study were to: (i) evaluate the potential for denitrification of NO₃⁻ and gaseous N evolution from soil in bioremediation of high NO₃⁻ groundwater in irrigated corn of the Central Platte Valley; (ii) evaluate if N₂O loss represented a potential threat to air quality; and (iii) examine the effects of several soil environmental factors on denitrification and N₂O emissions.

MATERIALS AND METHODS

Denitrification and gaseous emissions of N₂O and CO₂ were measured from 32 ha of pivot-irrigated corn (E1/2, NE1/4, E4/4, E5/4)
section 15, R13W, T9N) at the Management Systems Evaluation Area (MSEA) site near Shelton, NE, during the 1991 and 1992 growing seasons. The climate in the area is characterized with a monthly mean high and low temperature range of -5 to 25°C and a mean annual precipitation of 632 mm, and for the growing season (May through September), 340 mm. Soils at the experimental site are alluvial; Hord silt loam (Cumulic fine-silty mixed mesic Hapludoll) is the major soil series (84%) with some Hall silt loam (10%) and Wood River silt loam (6%) soils. Particle-size distribution of surface soil (0-7.6 cm) was 30% sand, 46% silt, and 24% clay. Soil pH was 6.8 and total C and N were 12.2 and 1.2 g kg$^{-1}$, respectively.

Finer-textured surface soil materials at this site are underlain by sand and gravel at depths of 0.46 to 1.22 m. This situation results in large potential for NO$_2$ leaching to groundwater, which in this area contains 32 mg NO$_2$-N kg$^{-1}$, but also a greater potential for denitrification because the finer-textured surface soils must become saturated before percolate will move into the sand and gravel layers below. Sampling schedules for gas flux measurements were adapted to concentrate sampling during periods when soils were wettest immediately after rainfall or irrigation and when N fertilizers were applied to soil directly or by fertigation. Water and N management practices for 1991 and 1992 are outlined in Table 1.

Corn hybrid (Pioneer Brand 3379) was planted, during the first week in May each year, on a 91 cm row spacing at a population of 73,000 plants ha$^{-1}$. Surface gas flux measurements were facilitated through installation of 15.3 cm diameter, 10 cm high PVC cylindrical rings to a depth of 7.6 cm, between and within crop rows, with treatments of with and without acetylene blockage that were spaced at least 3 m apart to avoid problems from acetylene diffusion. Samples taken before the growing season (preplant) in 1992 are considered interrow samples. Plot area size of each replicate was $9.1 \times 4.6$ m and measurements were replicated four times within the field. Locations of the plots for 1991 and 1992 were rotated between areas to avoid cumulative effects of acetylene. Gas flux measurements were taken two to four times each day by fitting the PVC cylinders with 1.93-L vented covers for 1-h intervals, during which time 13 mL gas samples were withdrawn in evacuated glass sampling vials and transported to the laboratory for gas chromatographic analysis of CO$_2$ using a Tracer (MT-220) gas chromatograph with a thermal conductivity detector and for N$_2$O using a Shimadzu (GC-14A) gas chromatograph fitted with an electron capture detector. Measurements of denitrification were made through addition of lightly coated calcium carbide (60% CaC$_2$ plus 40% wax consisting of 1/3 of vaseline and 2/3 of paraffin) to soil around and underneath a separate set of cylinders that generated acetylene and effectively blocked nitrification and the reduction of N$_2$O to N$_2$ during denitrification. Thus, measurement of N$_2$O flux from carbide-treated soils provided a direct estimate of soil denitrification. Details concerning the use of surface gas chambers, use of coated calcium carbide, and gas chromatographic analysis of CO$_2$ and N$_2$O are given by Aulakh et al. (1991) and Bronson et al. (1992).

Soil temperatures at a 5 cm depth were monitored continuously during the sampling period using bi-metal thermometers. Soil samples were taken to a 7.6 cm depth from areas adjacent to cylinders before each gas sampling period and from within cylinders after gas sampling for determination of bulk density, water content, WFPS, pH, and NH$_4^+$ and NO$_3^-$ levels. WFPS was calculated as ([gravimetric water content $\times$ soil bulk density]/total soil porosity), where soil porosity $= [1 -$ soil bulk density/2.65]) and 2.65 is the assumed particle density of soil. Soil was passed through a 2 mm sieve, mixed, and subsampled for soil chemical analysis. Soil pH of a 1:1 soil/water mixture was measured as described by Eckert (1988). Contents of NH$_4^+$ and NO$_3^-$ were determined using soil-KCl (2M) extracts (1:10) by the indophenol blue and the cadmium reduction techniques, respectively (Keeney and Nelson, 1982).

Standard deviation/error and paired t-test were computed for the data using the statistical analysis system (SAS Institute, 1992). Also, correlation relationships were investigated between denitrification, N$_2$O emissions, and various soil environmental factors as well as other measured parameters such as soil CO$_2$ flux.

**RESULTS**

Denitrification rates, N$_2$O flux, soil respiration (CO$_2$ flux), WFPS, and soil temperature at the experimental site are presented in Fig. 1–6. Denitrification and N$_2$O losses from soil in irrigated corn were low throughout most of the 1991 and 1992 growing seasons, ranging from 2 to 50 g N ha$^{-1}$ d$^{-1}$, when surface soils were generally dry and <60% of the soil pore space was water-filled, especially in the drier 1991 season (Fig. 7). Nitrous oxide was the major measured gaseous N product under these conditions, presumably a product of nitrification and not denitrification. When soils were wetted by irrigation or rainfall to >70% WFPS, denitrification losses ranged from 0.1 to 1.4 kg N ha$^{-1}$ d$^{-1}$, with N$_2$O comprising 80 to 98% of denitrification gases measured (Fig. 1, 4, 5, and 6). Nitrous oxide was the major gaseous product lost from soil during the dry 1991 season but a minor component of gases lost during the normal 1992 season. The ratio of N$_2$O flux (without acetylene inhibition) to denitrification (with acetylene inhibition) was greater in the drier 1991 growing season than in the 1992 growing season (Fig. 8).

The average monthly N$_2$O emission from soil in the drier 1991 season ranged from 10 to 25 g N ha$^{-1}$ d$^{-1}$. This was much greater than that emitted in the 1992 season of normal precipitation that was only 2 to 12 g N ha$^{-1}$ d$^{-1}$. Total seasonal N losses via denitrification and N$_2$O emission were estimated at 3.6 and 2.3 kg N ha$^{-1}$, respectively, during the relatively dry 1991 growing season. These losses represented about 1 to 1.5% of the N applied as fertilizer or in irrigation water. In the normal 1992 growing season, denitrification losses increased to 7.5 kg N ha$^{-1}$ which represented 4.9% of

<table>
<thead>
<tr>
<th><strong>Table 1. Water and N management and N removed in grain for 1991 and 1992 at the MSEA center pivot buffer area.</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1991—Dry year, May-Sept. ppt. = 239 mm</strong></td>
</tr>
<tr>
<td><strong>Fertilizer N applied</strong></td>
</tr>
<tr>
<td><strong>Anhydrous injection (4/15)</strong></td>
</tr>
<tr>
<td><strong>UAN; sidedress (5/9)</strong></td>
</tr>
<tr>
<td><strong>Irrigation, 310 mm</strong></td>
</tr>
<tr>
<td><strong>32 mg kg$^{-1}$ NO$_3^-$</strong></td>
</tr>
<tr>
<td><strong>Total N inputs</strong></td>
</tr>
<tr>
<td><strong>Corn grain yield, dry wt. 10.36 Mg ha$^{-1}$ (1.37% N)</strong></td>
</tr>
<tr>
<td><strong>1992—Normal year, May-Sept. ppt. = 319 mm</strong></td>
</tr>
<tr>
<td><strong>Fertilizer N applied</strong></td>
</tr>
<tr>
<td><strong>NH$_4^+$-P sidedress (5/1)</strong></td>
</tr>
<tr>
<td><strong>Fertilization, three times</strong></td>
</tr>
<tr>
<td><strong>UAN (6/29, 7/1, 7/6)</strong></td>
</tr>
<tr>
<td><strong>Irrigation, 191 mm</strong></td>
</tr>
<tr>
<td><strong>32 mg kg$^{-1}$ NO$_3^-$</strong></td>
</tr>
<tr>
<td><strong>Total N inputs</strong></td>
</tr>
<tr>
<td><strong>Corn grain yield, dry wt. 10.32 Mg ha$^{-1}$ (1.17% N)</strong></td>
</tr>
</tbody>
</table>

**Notes:**

- Irrigation in <25 mm increments.
- Urea-ammonium nitrate.

**Table 1. Water and N management and N removed in grain for 1991 and 1992 at the MSEA center pivot buffer area.**
Fig. 1. Denitrification, N₂O flux, soil respiration, WFPS, and temperature (5 cm soil depth) at the Experimental site for 9-10 May and 5-7 June 1991. * Indicates significant difference ($P = 0.05$) between row and interrow.
Fig. 2. Denitrification, N₂O flux, soil respiration, WFPS, and temperature (5 cm soil depth) at the Experimental site for 24-27 June and 8-12 July 1991. Arrows denote hand irrigation with 2.5 cm H₂O at 1000 h 26 June, 1 cm rain on night of 8 July and pivot irrigation of 1.7 cm of high NO₃ water (32 mg NO₃-N L⁻¹) at 1700 h on 10 July 1992. * Indicates significant difference (P = 0.05) between row and interrow.
the N applied in fertilizer and irrigation water (Table 2). Estimates of seasonal denitrification and N\textsubscript{2}O emissions were determined by linearly interpolating data points for each day based on wetting and fertilization events as well as soil temperature according to the gas flux measurements from different gas sampling periods (Fig. 1–6), and integrating the area under the points for each day over the corn-growing period (May–September) by Simpson’s Rule (Bronson et al., 1992; Hanson et al., 1994). Assumptions associated with these estimates were: (i) the simulated gas flux measurements represented the flux at field scale under natural field conditions and current field management practice; and (ii) the gas flux variations between wetting or fertilization events were gradual or steady which were similar to that of gas sampling intervals.

Significant denitrification losses from surface soil only occurred over relatively short periods of time (1 to 2 d) when soils were wet to >70% WFPS and surface soil NO\textsubscript{3} concentrations exceeded 5 to 10 kg N ha\textsuperscript{-1} (Table 3). The rapid decline of soil water content after wetting was probably the major reason that significant denitrification losses only occurred during short periods of time. Therefore, although soil temperature and NO\textsubscript{3} concentrations were adequate to support denitrification activity, the process was apparently minimized by rapid downward and lateral movement of the irrigation or rain water into drier surrounding soil, which prevented development of anaerobic conditions. Rates of denitrification and N\textsubscript{2}O production were similar for row and interrow locations and differed significantly according to paired t-tests (indicated as * above points on curves in Fig. 1–6) only when the soil physical conditions and amounts of NO\textsubscript{3} and NH\textsubscript{4} were different because of sidedress fertilizer applications and planting operations, or later in the growing season when soil density and water status varied between these row locations.

DISCUSSION

Total seasonal N losses via denitrification and N\textsubscript{2}O emission were estimated at about 1 to 4.9% of the N applied as fertilizer or in irrigation water in the dry to normal growing seasons. This compares with results of Mosier et al. (1986), who reported that 2.5% of N fertilizer applied was emitted as N\textsubscript{2} + N\textsubscript{2}O, and indicates that denitrification is not a major pathway for fertilizer N loss in irrigated corn in semiarid and subhumid regions (Bronson et al., 1992). Guenzi et al. (1994) reported that total gaseous loss of N oxides during the growing season of corn probably did not exceed 1% of the fall-applied N fertilizer. Similar results were also reported for different cropping systems by Svensson et al. (1991) indicating that the rates of denitrification accounted for about 3 to 5% of the N fertilizer applied to barley (Hordeum vulgare L.), and from 2 to 7% of that applied to grass ley over a 2-yr period. Differences between those 2-yr results were mainly due to the variation of soil water content during the test periods.
Fig. 4. Denitrification, N₂O flux, soil respiration, WFPS, and temperature (5 cm soil depth) at the Experimental site for 28-29 Apr. and 12-14 May 1992. Arrows denote hand irrigation with 2.5 cm low NO₃⁻ water (<3 mg NO₃⁻·N·L⁻¹) at 1400 h on 28 April and at 1400 h on 12 May, 0.25 cm rain and pivot irrigation with 1.5 cm high NO₃⁻ water (32 mg NO₃⁻·N·L⁻¹) at 3000 h on 13 May 1992.
In our study, the average monthly N$_2$O emission from soil ranged from 2 to 25 g N ha$^{-1}$ d$^{-1}$, which accounted for approximately 1% of N applied to soil in fertilizer and irrigation water. Eichner (1990) evaluated available data from various field experiments and estimated that 2% of N fertilizer is lost as N$_2$O annually in fertilized
Fig. 6. Denitrification, N₂O flux, soil respiration, WFPS, and temperature (5 cm soil depth) at the Experimental site for 20-23 July and 17-20 Aug. 1992. Arrows denote hand application of 2.5 cm of high NO₃⁻ irrigation water (32 mg N L⁻¹) at 0900 h on 21 July, 2.8 cm rain at 2300 h on 21 July, pivot irrigation with 2.3 cm of high NO₃⁻ irrigation water at 1400 h on 17 August, 0.25 cm rain the night of 17 August, and hand irrigation of 1.3 cm of high NO₃⁻ irrigation water at 0900 h on 18 Aug. 1992.

and manured soils. Williams et al. (1992) summarized N₂O emissions from different land areas and found that they varied from 2.4 to 136 g ha⁻¹ d⁻¹ in agricultural fields, <1 to 54 g ha⁻¹ d⁻¹ in grassland and savanna areas, and 0.03 to 5.5 g ha⁻¹ d⁻¹ in temperate and tropical forests. The amount of N₂O emitted from corn
cropping systems ranges from 0 to 26 g ha\(^{-1}\) d\(^{-1}\) in semiarid regions (Guenzi et al., 1994), and from 24 to 208 g ha\(^{-1}\) d\(^{-1}\) in subhumid regions (Anderson and Levine, 1987). Nitrous oxide losses as a percentage of the N applied to corn vary from 1.2 to 2% (Anderson and Levine, 1987; Duxbury and McConnaughey, 1986; Mosier and Hutchinson, 1981). Average monthly N\(_2\)O loss from soil in our study varied from 10 to 25 g N ha\(^{-1}\) d\(^{-1}\) in the drier 1991 season but from only 2 to 12 g N ha\(^{-1}\) d\(^{-1}\) in the 1992 season of normal rainfall, indicating N\(_2\)O was the major gaseous N product under drier soil conditions, presumably a product of nitrification and not denitrification. Although some of the emitted gaseous N oxides may have been produced by heterotrophic denitrifiers active in anaerobic microsites, it is likely that most was produced by autotrophic-nitrifying bacteria, which represent the predominant source of gaseous N oxides in well-aerated soils (Tortoso and Hutchinson, 1990).

Soil respiration (CO\(_2\) flux) rates ranged from 4.5 to 33 and 1 to 38 kg CO\(_2\)-C ha\(^{-1}\) d\(^{-1}\) in 1991 and 1992, respectively, and varied with soil water status and soil temperature. The soil CO\(_2\) flux measured in this study represents the total of microbial and plant root respiration. However, measurements made during times when plants were not present, from between row areas early in the growing season, and in a separate greenhouse study for corn grown in intact soil cores (Qian and Doran, 1996; Qian et al., 1997) indicate that the contribution to soil CO\(_2\) flux from root respiration represents <33% of the total flux and that the majority (>67%) results from microbial metabolism of root-derived C and soil organic matter. According to the stoichiometric relationship of the denitrification reaction, 1 kg of available C is required for production of 1.17 kg N as N\(_2\)O or 0.93 kg N as N\(_2\) (Burford and Bremner, 1975). Calculations from these values show that 0.86 and 1.0 kg of available C were required in 1991 and 1992, respectively, to produce 1 kg N as N\(_2\)O + N\(_2\) in which the ratio of N\(_2\)O-N to (N\(_2\)O + N\(_2\))-N is the average of ratios for 1991 (0.97) and 1992 (0.31), respectively (Fig. 8). Based on the denitrification rates measured, the CO\(_2\) produced from maximum denitrification rates ranged from 0.03 to 0.22 and 0.01 to 1.4 kg CO\(_2\)-C ha\(^{-1}\) d\(^{-1}\), which account for only 0.7 and 1 to 3.7% of total soil CO\(_2\) flux measured in 1991.
Table 2. Average, maximum fluxes, and seasonal N losses of denitrification and nitrous oxide gases from irrigated corn at the MSEA center-pivot buffer area near Shelton, NE in 1991 and 1992.

<table>
<thead>
<tr>
<th>Season</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>Seasonal loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gas flux, g N ha⁻¹ d⁻¹</td>
<td>gas flux, g N ha⁻¹ d⁻¹</td>
<td>monthly losses, kg N ha⁻¹</td>
<td>monthly losses, kg N ha⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denitrification</td>
<td>10 (70)</td>
<td>10 (250)</td>
<td>30 (30)</td>
<td>40 (40)</td>
<td>3.60 (1.5%)†</td>
<td>2.29 (1.0%)‡</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>25 (25)</td>
<td>10 (125)</td>
<td>15 (15)</td>
<td>20 (20)</td>
<td>0.59</td>
<td>1.52 (1.0%)</td>
</tr>
<tr>
<td>Denitrification</td>
<td>0.32</td>
<td>0.79</td>
<td>0.92</td>
<td>1.57</td>
<td>7.48 (4.9%)</td>
<td></td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>0.60</td>
<td>0.61</td>
<td>0.50</td>
<td>0.37</td>
<td>0.43</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

† Values in parentheses represent maximum flux measured.
‡ 1991-239 mm growing season rainfall and 310 mm irrigation in <25 mm increments, 1992-319 mm growing season rainfall and 191 mm irrigation in <25 mm increments.
§ Values in parentheses represent loss as % of N applied in fertilizer and irrigation water; 234 and 153 kg N ha⁻¹ applied in 1991 and 1992, respectively.

Table 3. Soil NO₃⁻ and NH₄⁺ contents (kg N ha⁻¹) for 0–7.6 cm surface layer at the end of gas sampling for denitrification and N₂O emission.

<table>
<thead>
<tr>
<th>Sampling date</th>
<th>C₂H₂</th>
<th>NO₃⁻</th>
<th>NH₄⁺</th>
<th>NO₂</th>
<th>NH⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interrow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9-10 May</td>
<td>+</td>
<td>3.0</td>
<td>0.7</td>
<td>38.0</td>
<td>30.0</td>
</tr>
<tr>
<td>5-7 June</td>
<td>-</td>
<td>37.5</td>
<td>19.5</td>
<td>93.3</td>
<td>197.0</td>
</tr>
<tr>
<td>24-27 June</td>
<td>+</td>
<td>8.4</td>
<td>1.0</td>
<td>13.7</td>
<td>2.0</td>
</tr>
<tr>
<td>8-12 July</td>
<td>-</td>
<td>18.7</td>
<td>5.0</td>
<td>20.0</td>
<td>0.0</td>
</tr>
<tr>
<td>12-15 Aug.</td>
<td>+</td>
<td>3.0</td>
<td>2.4</td>
<td>9.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Within-row</td>
<td>-</td>
<td>36.0</td>
<td>0.0</td>
<td>28.0</td>
<td>0.2</td>
</tr>
<tr>
<td>28-29 Apr.</td>
<td>+</td>
<td>6.0</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12-14 May</td>
<td>+</td>
<td>5.0</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1-4 June</td>
<td>+</td>
<td>10.0</td>
<td>2.6</td>
<td>9.0</td>
<td>3.3</td>
</tr>
<tr>
<td>29 June-2 July</td>
<td>-</td>
<td>16.0</td>
<td>0.1</td>
<td>0.5</td>
<td>2.6</td>
</tr>
<tr>
<td>20-23 July</td>
<td>-</td>
<td>29.0</td>
<td>7.0</td>
<td>30.0</td>
<td>3.4</td>
</tr>
<tr>
<td>17-20 Aug.</td>
<td>+</td>
<td>3.9</td>
<td>1.9</td>
<td>10.0</td>
<td>2.5</td>
</tr>
<tr>
<td>1992</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† ++ = with acetylene blockage; -- = without acetylene blockage.
ever, were not consistently correlated with denitrification rate (Table 3, Fig. 1–6), except for general seasonal trends, that is, monthly gaseous N losses by denitrification increased during the corn growing season reaching a maximum in August (Table 2). Wheatly and Williams (1989) found similar seasonal patterns and a similar lack of relationships between soil temperature, water content, and denitrification activity. They also concluded that C availability may be a more important regulator of denitrification activity under field conditions than previously thought. Indirect evidence presented by Myrold and Tiedje (1985) suggested that denitrification capacity and total microbial biomass were increased only by C addition; differences in NO\textsubscript{3}\(^-\) concentration and soil water content had no effect in their experimental soil at two concentrations of NO\textsubscript{3}\(^-\) (0 and 100 mg N kg\(^{-1}\) soil) and two water contents (0.23 and 0.28 g H\(_2\)O g\(^{-1}\) soil) throughout the duration of incubation. However, at the %WFPS levels present in this study (50 and 61 %, respectively), denitrification would not be a predominant process according to Linn and Doran (1984). Groffman and Tiedje (1991) also showed that soil water content did not account for the majority of variability in denitrification activity in any of the soils studied consisting of different soil texture (loam, clay loam, and sand) and different drainage classes (well-, somewhat-poorly, and poorly drained). Denitrification activity was also not strongly predicted or controlled by soil NO\textsubscript{3}\(^-\) concentration or soil temperature in north temperate forest soils with NO\textsubscript{3}\(^-\) concentrations ranging from 0.12 to 2.48 (average 0.58) mg N kg\(^{-1}\) dry soil (Groffman and Tiedje, 1989, 1991). Rates of both denitrification and CO\textsubscript{2} production were greatest in early spring and declined in summer, suggesting negative relationship between temperature and activity. Schnabel and Stout (1994) have also reported a similar lack of relationship between measured NO\textsubscript{3}\(^-\) concentration, temperature, water content, and denitrification activity from ryegrass fields of well-drained and poorly drained floodplain soils.

The lack of correlation between denitrification and the major controlling factors has been attributed to spatial and temporal variations but may also result from gas entrapment in soil at greater water contents and failure to measure denitrification products under wet conditions. In our study, greater soil water contents apparently reduced N\(_2\)O diffusion through the silt loam soil which resulted in a considerable lag between wetting events and the "measurement" of elevated rates of denitrification (Fig. 1–6). This observation was supported by the better correlations between denitrification and N\(_2\)O emissions and %WFPS 24 h before measurements (Fig. 10). There also appears to be a great lag from N fertigation/fertilization to the increased denitrification rates. In both cases, denitrification rates remained elevated after rainfall/irrigation or fertilization for only a short period. Diffusion of N gases (N\(_2\)O and N\(_2\)) and CO\textsubscript{2} are governed by a variety of factors, such as tortuosity of the soil matrix and air pore volume. The N\(_2\)O formed, diffusing through

---

**Fig. 9.** Logarithmic relation of denitrification and N\(_2\)O emission rates vs. % WFPS for 1991.

**Fig. 10.** Logarithmic maximum denitrification and N\(_2\)O emission rates vs. % WFPS 24 h earlier for 1992.
the soil pores, may be entrapped in soil aggregates (Kemper et al., 1985), dissolved in the soil water (Minnami, 1987), sorbed on clay minerals and organic substances (Chalamet, 1990), or be lessened by microbial reduction to N₂ (Slater and Capone, 1989; Simarmata et al., 1991). Even in the presence of acetylene, some N₂O can be reduced to N₂ (Simarmata et al., 1993).

Soil pH changes over the growing season in 1992 were mainly associated with fertilization, especially ammonium-phosphate sidedress (Fig. 11), indicating active nitrification occurred after ammonium-N application. Within-row areas showed a greater pH decline than that of interrow areas, possibly resulting from more active root exudation and acidification from more fertilizer N in the row due to the ammonium-phosphate sidedress. Soil pH increased to around 7.5 with no difference between row and interrow at late growing season suggesting a change of equilibrium between pH and carbonate or bicarbonate in the soil and possibly the hydrolysis of urea applied uniformly with irrigation water. There was no significant difference in soil pH between initial and final times of sampling for denitrification or between acetylene treated and untreated areas as indicated by the error bars in Fig. 11.

CONCLUSIONS

Seasonal gaseous N losses via denitrification and N₂O emission from irrigated corn during a relatively dry 1991 season were 3.6 and 2.3 kg N ha⁻¹, respectively, which represented 1 to 1.5% of N applied as fertilizer or in irrigation water. Denitrification losses during the wetter 1992 season increased to 7.5 kg N ha⁻¹ which represented 4.9% of N applied as fertilizer or in irrigation water. Poor correlations existed between denitrification, N₂O emissions and various soil environmental factors, as well as soil respiration, except soil WFPS which provides a good prediction of denitrification given adequate available C and NO₃⁻ supply. Relatively low gaseous N losses from denitrification and N₂O emissions from irrigated corn on this alluvial soil suggest little additional threat to atmospheric quality or N-use efficiency with good water and N management practices but also afford little hope for bioremediation of high-NO₃ groundwater (32 mg kg⁻¹) under existing management. These findings are in agreement with other research at this site (Kessavalou et al., 1996; Weier et al., 1994) which indicated that better water and N management practices are the preferred and most efficient long-term solution to preventing and alleviating groundwater contamination.

REFERENCES


irrigated corn in central Nebraska. J. Environ. Qual. 25:1008–
1014.
Linn, D.M., and J.W. Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-
Minami, K. 1987. Emission of nitrous oxide (N₂O) from agroecosy-
Qian, J.H., J.W. Doran, and D.T. Walters. 1997. Maize plant contribut-
ions to root zone available C and microbial transformations of nitrogen. Soil Biol. Biochem. (In press.)
able organic waste injected into soil. Soil Sci. Soc. Am. J. 52:
102–108.
Svensson, B.H., L. Klemetsson, S. Simkins, K. Paustian, and T. Rosswall. 1991. Soil denitrification in three cropping systems char-
Tortoso, A.C., and G.L. Hutchinson. 1990. Contributions of autotro-