Evaluation of Selected Processes Controlling Nitrogen Loss in a Flooded Soil

K. R. REDDY, W. H. PATRICK, JR., AND R. E. PHILLIPS

ABSTRACT

The roles of NH₄-N diffusion, NH₄-N oxidation, NO₃-N diffusion, and NO₃-N reduction in controlling N loss from continuously flooded soil were evaluated in independent experiments. Ammonium-N moved from zones of high NH₄-N concentration to the zones of low NH₄-N concentration. The average diffusion coefficient (D) for NH₄-N in flooded soil ranged from 0.059 to 0.216 cm² day⁻¹ for different soils. Diffusion coefficients were influenced by soil type and soil-water content. Rate of NH₄-N oxidation in the aerobic layer of flooded soil range from 1.2 to 3.5 µg g⁻¹ day⁻¹ in different soils. Nitrate diffusion into the anaerobic soil layer ranged from 0.96 to 1.91 cm² day⁻¹, whereas NO₃-N reduction rates were 0.32 to 0.52 day⁻¹. The slow rate of NH₄-N diffusion from the anaerobic soil layer to the aerobic soil layer and the slow rate of NH₄-N oxidation in the aerobic soil layer indicate that these two processes are limiting steps in controlling N loss. Nitrate diffusion into the anaerobic soil layer and NO₃-N reduction in the anaerobic soil layer were found to proceed at a faster rate and are not likely to limit N loss from flooded soil.

Additional Index Words: Ammonium diffusion, ammonium oxidation, nitrate diffusion, nitrate reduction, floodwater, waterlogged soils.


NITROGEN REACTIONS in flooded soil are greatly influenced by the presence of O₂ in the atmosphere overlying floodwater. This O₂ moves through the floodwater and reaches the soil surface, thereby causing the floodwater and the soil surface to be oxidized. The thickness of the aerobic soil layer (also called oxidized or nitrification zone) depends on the rate of O₂ movement through the floodwater and soil and the rate of O₂ consumption by the soil. Generally, the thickness of this layer varies from a few mm in soils of high biological activity to 1 to 2 cm in soils of low biological activity. Underlying the aerobic soil layer is the anaerobic soil layer (also called reduced or denitrification zone), which is devoid of O₂.

The major inorganic form of N in flooded soil is NH₄N. Ammonium N present in the surface aerobic soil layer can be readily oxidized to NO₃-N. The NO₃-N thus formed during the nitrification moves down into the anaerobic soil layer and undergoes denitrification. Several research workers, namely Pearsall (1950), Matsui (1954), Patnaik (1965), Patrick and Tusneem (1972), Patrick and Delaune (1972), and Chen et al. (1972), have reported this mechanism of N loss in flooded soils and sediments. More recently, Reddy et al. (1976) and Patrick and Reddy (1976) have demonstrated N loss due to the sequential process of NH₄-N diffusion from the anaerobic soil layer to the overlying aerobic soil layer, oxidation of NH₄-N in the aerobic soil layer, NO₃-N diffusion from the aerobic soil layer to the anaerobic soil layer, followed by the reduction of NO₃-N to gaseous end products. Although the rate of each of these processes in determining N loss was identified in an indirect way, their relative rates were not determined quantitatively. The objectives of the present investigation were to evaluate (i) the rate of NH₄-N diffusion from the anaerobic layer to the aerobic layer, (ii) the rate of NH₄-N oxidation in the aerobic soil layer, (iii) the rate of NO₃-N diffusion down to the anaerobic layer, and (iv) the rate of NO₃-N reduction in the anaerobic soil layer. Schematic presentation of these processes are shown in Fig. 1.

MATERIALS AND METHODS

The soils used in the present study were Crowley silty loam (fine, montmorillonitic, thermic Typic Hapludalfs); Midland silty clay loam (fine, montmorillonitic, thermic Vertic Ochraqualfs) obtained from the Rice Experiment Station, Crowley, La.; Mhoon silty clay loam (fine-silty, mixed, nonacid, thermic Typic Fluvaquents); and Commerce silty clay loam (fine-silty, mixed, nonacid, thermic Aeric Fluvaquents) obtained from the Mississippi River flood-plain near Baton Rouge, La. Gallion sandy loam (fine-silty, mixed, thermic Typic Hapludalfs) was obtained from the Ouachita River flood-plain near Monroe, La. The soils were air-dried, ground to pass through a 10-mesh sieve, mixed thoroughly, and stored in a tightly sealed container. For each independent study, a subsample of the soil was taken and ground to pass through a 40-mesh sieve. Selected physical and chemical properties of these soils are shown in Table 1. The N source used in the experiments was either ammonium sulfate or potassium nitrate, which was thoroughly mixed with the soil. This was accomplished by mixing the N source with a small amount of soil in a porcelain mortar and then mixing this with a larger amount of soil to obtain the desired concentration of NH₄-N or NO₃-N. Later, the soil containing the N

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Fig. 1—Schematic presentation of the processes evaluated in the study.
were then added to the cylinder containing 20 ml of distilled water; and then 50 g of soil containing 200 μg N/g of soil was used only in NH₄-N oxidation study. Later used as support to push the soil from the PVC cylinder for sectioning. Fifty grams of soil were sliced into 2-mm sections and analyzed for NH₄-N concentration as described in Experiment I and incubated for 2, 4, 7, 15, 30, and 60 days. At the end of each incubation period, the soil columns were sliced into 2-mm sections and analyzed for NH₄-N concentration as described in Experiment I.

**Ammonium-N Diffusion**

*Experiment I—* This experiment was designed to measure the diffusion and flux of NH₄-N from a zone of high concentration (anaerobic soil layer) to a zone of low concentration (aerobic soil layer) in a flooded soil. The soil was incubated under an anaerobic atmosphere above the floodwater. The NH₄-N concentration gradient was established by adding 200 μg N/g of soil as NH₄-N in the lower zone of the soil column (Zone A) as shown in Fig. 2 and no N added in the upper zone of the soil column (Zone B). The soil was incubated in open-end PVC cylinders (4.8-cm i.d. and 10-cm length). A mixture of paraffin wax and petroleum jelly (2:1 ratio) was poured into the bottom of each cylinder to provide a 1-cm thick base, which was later used as support to push the soil from the PVC cylinder for sectioning. Fifty grams of soil containing 200 μg N/g of soil were then added to the cylinder containing 20 ml of distilled water. The soil was allowed to settle for 30 min; an additional 20 ml of distilled water was added to the core; and then 50 g of untreated soil (with no added N) were added. The total length of the soil column was 4.8 cm. Finally, 60 ml of distilled water were added to provide 2.5 cm of overlying floodwater. The bulk density of the soil was 1.14 g/cm³, and the moisture content was 47% by weight and 54% by volume. The cylinders were then placed in a larger flask that was purged with argon. The anaerobic atmosphere prevented the formation of an aerobic soil layer. The Crowley soil column was allowed to equilibrate for 0, 1, 2, 4, 8, 15, 30, and 60 days in darkness at 28°C, whereas Midland and Mhoon soil columns were equilibrated for 2 days. At the end of each period, the soil columns were sliced into 2-mm sections, and the vertical distribution of NH₄-N was measured in the soil column. The initial distribution curve of NH₄-N obtained at the start of the incubation was subtracted from the distribution curves obtained at various incubation times. The diffusion coefficient (D) values were calculated from 2-day incubation periods for all three soil types as described below. The sectioning of the soil columns was carried out by the method described by Reddy and Patrick (1976).

*Experiment II—* This study was designed to show the effect of nitrification in the aerobic layer on NH₄-N removal from the anaerobic zone. An aerobic soil layer was developed by incubating the Crowley soil column under air (21% O₂). Soil columns were prepared as described in Experiment I and incubated for 2, 4, 7, 15, 30, and 60 days. At the end of each incubation period, the soil columns were sliced into 2-mm sections and analyzed for NH₄-N concentration as described in Experiment I.

*Experiment III—* This study was conducted to determine the effect of NH₄-N concentration on NH₄-N diffusion rate. The soil type used in this study was Crowley silt loam. The procedure used in this study was the same as described in Experiment I. The NH₄-N concentration used in this study were 50, 100, and 200 μg N/g of soil. The soil columns (in duplicate) were incubated for a period of 2 days under anaerobic conditions. At the end of the incubation period, the soil columns were sliced into 2-mm sections and analyzed for NH₄-N concentrations, and diffusion coefficients were determined.

*Experiment IV—* This study was designed to determine the effect of soil moisture content on NH₄-N diffusion in Crowley silt loam. The soil moisture content used in this study was 0.06, 0.11, 0.27, and 0.54 cm³/cm³. Nitrification inhibitor [2-chloro-6-(trichloromethyl)pyridine] was used to prevent NH₄-N oxidation in all treatments. The soil columns were incubated for a period of 15, 15, 7, and 2 days for treatments with soil moisture content of 0.06, 0.11, 0.27, and 0.54 cm³/cm³, respectively. All soil columns were incubated under aerobic (21% O₂) atmosphere. At the end of incubation, the soil columns were sliced into 2-mm sections and analyzed for NH₄-N concentration, and diffusion coefficients were calculated.

**Calculation of Diffusion Coefficients**

The geometry of the system used for calculation of NH₄-N diffusion in Experiments I, III, and IV was the same as that described by Phillips and Brown (1964). The loss in terms of mass balance is given by the total quantity of ions remaining in the soil, mg/cm³; and h = length of soil column (cm) initially containing NH₄-N; R = ratio of (Qₐ + Q₂)/Q₁; Q₁ = total quantity of ions diffused, μg/cm³; Q₂ = total quantity of ions remaining in the soil, μg/cm³; and t = time (days).

where

\[ D = \frac{\pi h^2 R^2}{t} \]

Ammonium N Oxidation

*Experiment V—* Soil types used in this study were Crowley, Mhoon, Midland, Commerce, and Gallion. Five-hundred grams of each soil were mixed with an equal amount of distilled water and stirred continuously for 6 days while air (21% O₂) was passed through the soil.

*a* The diffusion coefficients (D) for NH₄+ reported in this manuscript are actually the apparent diffusion coefficients divided by the retardation factors. The retardation factor is \( \frac{1 + \rho \cdot K_d}{\theta} \) where \( \rho \) = soil bulk density, g/cm³; \( K_d \) = distribution coefficient relating the concentration of NH₄+ adsorbed on cation exchange sites to that in the soil solution, cm³/g; and \( \theta \) = volumetric soil water content, cm³/cm³. The retardation factor for the soils reported would be expected to be different.
was bubbled through the suspension to maintain aerobic conditions. The soil suspension was then treated with a known amount of $^{15}$N as ammonium sulfate enriched with 5.036 atom % $^{15}$N excess. A known amount of soil suspension was transferred to several wide mouth bottles to obtain a 1-cm thick oxygenated soil layer. Experience has shown that preincubation in air (21% O$_2$) prevented the development of anaerobic conditions in a thin layer (< 2 cm) of soil. The soil column was maintained under saturated conditions with no excess floodwater. The samples were incubated for a period of 0, 4, 8, 15, 30, and 60 days and then analyzed for labeled NH$_4$-N and NO$_3$-N. Redox potential (Eh) of the aerobic soil layer was measured after a 24-hour equilibration period by inserting a platinum electrode in the soil.

**Nitrate Diffusion**

*Experiment VI*—This experiment was designed to show the movement of NO$_3$-N from the overlying floodwater (where a large supply of NO$_3$-N was maintained) into the underlying soil layer. One-hundred and fifty grams of Crowley, Mhoon, and Midland soil with an equal amount of water containing 0.1% formaldehyde solution, were weighed into PVC cores (in duplicate) and incubated under anaerobic atmosphere for 5 days. Formaldehyde was used to suppress the denitrifying organisms. The overlying floodwater was treated with 300 $\mu$g NO$_3$-N per ml of floodwater as KNO$_3$ and incubated under anaerobic atmosphere for 5 days. The diffusion coefficient for NO$_3$-N moving in the overlying water into the underlying soil were calculated according to the following equation:

$$D = \frac{\pi F^2}{4C t^4}$$  \[2\]

where

- $D$ = diffusion coefficient of NO$_3$-N, cm$^2$/day;
- $F$ = total quantity of NO$_3$-N moved into the soil column per unit area of soil column, $\mu$g/cm$^2$;
- $C_0$ = initial concentration of NO$_3$-N at the soil surface; $\mu$g/cm$^2$; and
- $t$ = time (days).

The solution of $\Delta C/\Delta t = D\Delta C/\Delta x^2$ subject to the following initial and boundary conditions (Crank, 1956; Carslaw and Jagger, 1959):

$$C(0,t) = C_0; \quad C(x,0) = 0,$$

$$\lim_{x \to \infty} C(x,t) = 0$$  \[5\]

is

$$C(x,t) = C_0 \text{erfc} \left[ \frac{x(4Dt)^{1/2}}{4} \right]$$  \[6\]

Equation [2] can be found by carrying out the integration shown in Eq. [7]:

$$F = -D \int_0^t \frac{\partial C(0,t)}{\partial t} \, dt$$  \[7\]

where

- $F$ = total amount of NO$_3$-N diffusing per unit cross-sectional area across the plane at $x=0$ in time $t$, $\mu$g/cm$^2$;
- erfc = complimentary error function;
- $C$ = NO$_3$-N concentration, $\mu$g/cm$^2$;
- $C_0$ = initial concentration of NO$_3$-N, $\mu$g/cm$^2$;
- $x$ = depth of soil column, cm; and
- $t$ = time (days).

It is assumed that $C_0$ remains constant during the study period.

### Table 2—Effect of soil type on NH$_4$-N diffusion under flooded conditions.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>NH$_4$-N conc., $\mu$g/g</th>
<th>Diffusion coefficient, cm$^2$/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crowley</td>
<td>200</td>
<td>0.216</td>
</tr>
<tr>
<td>Midland</td>
<td>210</td>
<td>0.172</td>
</tr>
<tr>
<td>Mhoon</td>
<td>196</td>
<td>0.059</td>
</tr>
</tbody>
</table>

**Nitrate Reduction**

*Experiment VII*—This study was designed to measure the rate of NO$_3$-N loss in flooded Crowley and Mhoon soil. Twenty-five grams of soil (oven-dry basis) were transferred into test tubes containing enough nitrate N (100 $\mu$g/g of soil) solution to saturate the soil. Each of the test tubes was fitted with a rubber stopper having a serum cap and were purged with argon to create anaerobic conditions. Duplicate test tubes were removed at the end of 0, 1/2, 1, 2, 4, 6, 8, and 12 days and analyzed for NO$_3$-N.

**Analytical Methods**

Ammonium N was extracted from the soil samples after a 1-hour shaking with 2N KCl solution. During the filtration, the soils were washed with excess KCl solution. Ammonium N in the extracts was analyzed using steam distillation and NO$_3$-N by the phenoldisulfonic acid method, as described in detail by Bremner (1965a). Labeled N analysis was carried out on an isotope ratio mass spectrometer (Bremner, 1965b). Ammonium N in sectioned soil samples was analyzed by direct steam distillation using 2N KCl and MgO (Bremner, 1965a).

### RESULTS AND DISCUSSION

Ammonium Diffusion

Diffusion of NH$_4$-N from a soil zone of high concentration to a soil zone of low concentration was measured under flooded conditions in three different soils equilibrated under an anaerobic atmosphere for a period of 2 days. The diffusion coefficient ($D$) for NH$_4$-N diffusing in a saturated soil condition was estimated from the distribution curve using Eq. [1], as described by Phillips and Brown (1964). The $D$ values for three soil types are presented in Table 2. Ammonium N moved at a slower rate in Mhoon soil (0.059 cm$^2$/day or 0.68 $\times$ 10$^{-6}$ cm$^2$/sec) as compared to Midland soil (0.172 cm$^2$/day or 1.99 $\times$ 10$^{-6}$ cm$^2$/sec), and Crowley soil (0.216 cm$^2$/day or 2.51 $\times$ 10$^{-6}$ cm$^2$/sec). Slower diffusion rate in the Mhoon soil was probably due to higher cation exchange capacity and clay content as compared to Crowley and Midland soil. A similar $D$ value of 0.30 cm$^2$/day (3.5 $\times$ 10$^{-6}$ cm$^2$/sec) was also reported by Berner (1974) for NH$_4$-N moving in sediments containing 70% water. These $D$ values reported for wet soils and sediments are generally higher than the $D$ values of 0.0035 to 0.0259 cm$^2$/day (0.4 to 5.0 $\times$ 10$^{-7}$ cm$^2$/sec) for well-drained soils containing 5 to 30% volumetric moisture content (Clarke and Barley, 1968). The results we obtained for NH$_4$-N diffusion at various soil moisture contents (Table 3) indicated that the $D$ values decreased with a decrease in soil moisture content. The lowest $D$ value of 0.0038 cm$^2$/day (4.4 $\times$ 10$^{-8}$ cm$^2$/sec) was obtained for a soil moisture content of 0.06 cm$^3$/cm$^3$. As the soil moisture content increases, the liquid phase becomes more continuous and the diffusion path becomes less tortuous, resulting in more rapid movement of ions in the system. Also, as the soil moisture changes, the cation concentrations in

<table>
<thead>
<tr>
<th>Soil moisture, cm$^3$/cm$^3$</th>
<th>Bulk density, g/cm$^3$</th>
<th>Diffusion coefficient, cm$^2$/day</th>
<th>Incubation period, days</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>1.316</td>
<td>0.004</td>
<td>15</td>
</tr>
<tr>
<td>0.11</td>
<td>1.362</td>
<td>0.010</td>
<td>15</td>
</tr>
<tr>
<td>0.27</td>
<td>1.404</td>
<td>0.050</td>
<td>7</td>
</tr>
<tr>
<td>0.54</td>
<td>1.146</td>
<td>0.216</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil type</th>
<th>NH$_4$-N conc., $\mu$g/g</th>
<th>Diffusion coefficient, cm$^2$/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crowley</td>
<td>200</td>
<td>0.216</td>
</tr>
<tr>
<td>Midland</td>
<td>210</td>
<td>0.172</td>
</tr>
<tr>
<td>Mhoon</td>
<td>196</td>
<td>0.059</td>
</tr>
</tbody>
</table>
whereas a moisture content below saturation represents lowland rice field conditions, whereas a moisture content below saturation represents upland conditions. Similar results on the effect of soil moisture content on the diffusion of other ions were also reported by Phillips and Brown (1964, 1966), Rowell et al. (1967), Olsen and Kemper (1968), and Warncke and Barber (1972).

At low levels of NH₄-N added (< 100 µg/g) concentration of NH₄-N had very little effect on D values, whereas D values were slightly increased at 200 µg NH₄-N/g of soil added (Table 4). However, further experiments are needed to verify the effect of concentration on NH₄-N diffusion.

The distribution of NH₄-N following equilibrium for various time periods under anaerobic atmospheric conditions is presented in Fig. 3. During the early part of the incubation, the concentrations gradient of NH₄-N was of greater magnitude, resulting in rapid diffusion of NH₄-N. As the incubation period increased, the concentration gradient between the two zones decreased. At 60 days the distribution of NH₄-N was essentially complete. Diffusion of NH₄-N into the floodwater was not taken into consideration in the present study. However, analysis indicated very little NH₄-N in the floodwater, as would be expected because of the affinity of NH₄⁺ ions for the exchange complex.

In another study (Experiment II) where the atmosphere above the floodwater was aerobic (21% O₂), a similar trend of NH₄-N diffusion was observed up to a period of 15 days (Fig. 4). After this period, as a result of the presence of an aerobic surface layer, the accumulated NH₄-N in the surface soil layer was rapidly nitrified, resulting in a low NH₄-N concentration in the surface layer (Reddy et al., 1976).

### Table 4—Effect of NH₄-N concentration on NH₄⁺ diffusion in a flooded Crowley silt loam.

<table>
<thead>
<tr>
<th>Ammonium N concentration, µg/g of soil</th>
<th>Diffusion coefficient, cm²/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.147</td>
</tr>
<tr>
<td>100</td>
<td>0.148</td>
</tr>
<tr>
<td>200</td>
<td>0.216</td>
</tr>
</tbody>
</table>

### Table 5—Rate of NH₄-N oxidation in the aerobic soil layer with no excess floodwater.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>pH</th>
<th>EA mV</th>
<th>NH₄-N concentration, µg/g</th>
<th>Rate constant † calculated from total NH₄-N, µg g⁻¹ day⁻¹</th>
<th>Rate constant † calculated from labeled NH₄-N, µg g⁻¹ day⁻¹</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crowley</td>
<td>5.6</td>
<td>667</td>
<td>2.07</td>
<td>0.991</td>
<td>2.04</td>
<td>0.99</td>
</tr>
<tr>
<td>Mhoon</td>
<td>4.7</td>
<td>692</td>
<td>2.77</td>
<td>0.99</td>
<td>3.83</td>
<td>0.93</td>
</tr>
<tr>
<td>Midland</td>
<td>5.6</td>
<td>637</td>
<td>1.53</td>
<td>0.99</td>
<td>1.87</td>
<td>0.99</td>
</tr>
<tr>
<td>Commerce</td>
<td>5.3</td>
<td>642</td>
<td>2.31</td>
<td>0.94</td>
<td>2.64</td>
<td>0.96</td>
</tr>
<tr>
<td>Gallion</td>
<td>4.1</td>
<td>622</td>
<td>1.10</td>
<td>0.94</td>
<td>1.20</td>
<td>0.94</td>
</tr>
</tbody>
</table>

† Calculated from the decrease in NH₄-N concentration. ‡ Number of observations for each soil = 6.

### Ammonium Oxidation

Nitrification is another process that controls the N loss in a flooded soil. This is a biological reaction and involves organisms that are strictly aerobic and functions only in the presence of O₂ (Alexander, 1965). The rate of NH₄-N oxidation is dependent on the number of nitrifying bacteria and the abundance of O₂ in the surface soil layer. The optimum percentage of O₂ for rapid NO₃-N production in soil is similar to that found in air (Grechin and Cheng, 1960) and low or unnaturally high partial pressure of O₂ limit the activity of organisms. This means the nitrification rates of well-aerated soils cannot be compared with the nitrification rates of the aerobic soil layer of a flooded soil. The aerobic soil layer is saturated with water, and O₂ decreases with depth until it reaches zero at the aerobic-anaerobic interface.

The results obtained in this study on rates of NH₄-N oxidation in the aerobic soil layer are presented in Table 5. Ammonium oxidation rates were calculated based on total NH₄-N and labeled NH₄-N. The rate of NH₄-N oxidation was best described by a linear regression analysis, indicating that NH₄-N oxidation follows zero-order kinetics. The rate constants (K) calculated for total NH₄-N oxidation ranged from 1.1 to 2.8 µg g⁻¹ day⁻¹ for the different soils. Using labeled NH₄-N, the rates for oxidation of NH₄-N ranged from 1.2 to 3.5 µg g⁻¹ day⁻¹. Several other researchers also showed NH₄-N oxidation to be independent of NH₄-N concentration (Anderson, 1965; DeMarco et al., 1967; Wild et al., 1971; Huang et al.,...
Table 6—Effect of soil type on NO\textsubscript{3}\textsuperscript{-N} diffusion under flooded conditions.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Diffusion coefficient, cm\textsuperscript{2}/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crowley</td>
<td>1.33</td>
</tr>
<tr>
<td>Midland</td>
<td>1.94</td>
</tr>
<tr>
<td>Mhoon</td>
<td>0.96</td>
</tr>
</tbody>
</table>

\(^{\dagger}C_{0} = 300 \mu g N/ml.\)

1974). Nitrification rates in these soils were probably influenced by low pH and aeration status. The Eh values of the 1-cm soil layer indicate aerobic conditions, but it is possible that oxygen concentration was probably low in the lower sections of the soil compared with the surface layer.

Nitrate N Diffusion

Nitrate N formed during the nitrification process in the aerobic soil layer readily diffuses both downward into the anaerobic layer and upward into the overlying floodwater, but net diffusion is downward. The measured \(D\) values for NO\textsubscript{3}-N diffusion were 1.33, 1.94, and 0.96 cm\textsuperscript{2}/day for Crowley, Midland, and Mhoon soils, respectively (Table 6). The high \(D\) values for

\[ \text{Aerobic atmosphere overlying floodwater} \]

![Graph of NH\textsubscript{4}-N concentration](image)

Fig. 4—Movement of NH\textsubscript{4}-N from the zones of high concentration to the zones of low concentration in the soil columns incubated under atmosphere above floodwater.

Table 7—Rate of denitrification reaction in the anaerobic soil layer.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>(NO\textsubscript{3}-N) (\mu g/g)</th>
<th>First-order rate constant (K), day(^{-1})</th>
<th>Half-life, days</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crowley</td>
<td>ND</td>
<td>0.315</td>
<td>2.2</td>
<td>0.978</td>
</tr>
<tr>
<td>Mhoon</td>
<td>112</td>
<td>0.630</td>
<td>1.3</td>
<td>0.985</td>
</tr>
<tr>
<td>Midland</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
</tbody>
</table>

\(^{\dagger} \text{ND} = \text{not determined.}\)

NO\textsubscript{3}-N are expected, because NO\textsubscript{3}-N is an anion and is not absorbed on the exchange complex and tends to move in the soil water. Romkens and Bruce (1964) measured \(D\) value of 1.15 cm\textsuperscript{2}/day \((1.33 \times 10^{-5} \text{ cm}^2/\text{sec})\) for NO\textsubscript{3}-N in silt having 42.7% moisture (by volume). Clarke and Barley (1968) reported that NO\textsubscript{3}-N moving in a well-drained soil (volumetric water content ranging 5 to 30%) has \(D\) values ranging from 0.043 to 0.42 cm\textsuperscript{2}/day \((0.5 - 5.0 \times 10^{-5} \text{ cm}^2/\text{sec})\), which is very low compared with the values obtained in the present study and by others. Comparing these values with the \(D\) values obtained for NH\textsubscript{4}-N, the NO\textsubscript{3}-N ions diffused much faster in a flooded soil as would be expected because of the greater cross section area of water in the pores of a saturated soil.

Nitrate Reduction

Nitrate reduction (denitrification) in flooded soils occurs in the anaerobic soil layer. Under flooded conditions, NO\textsubscript{3}-N is largely derived from oxidation of NH\textsubscript{4}-N in the surface aerobic soil layer and possibly in the water column. For NO\textsubscript{3}-N to be reduced into gaseous end products, it must diffuse down from the aerobic soil layer or overlying floodwater to the anaerobic soil layer. The actual rate of NO\textsubscript{3}-N reduction is dependent on three major processes that occur prior to NO\textsubscript{3}-N reduction: NH\textsubscript{4}-N diffusion, NH\textsubscript{4}-N oxidation, and NO\textsubscript{3}-N diffusion. The amount of energy source and number of denitrifying organisms present in the anaerobic soil layer also affects the NO\textsubscript{3}-N reduction process. The rate of NO\textsubscript{3}-N disappearance was best described by first-order kinetics (Table 7).

In an earlier study (Reddy et al., 1978), it was found that when carbon was limiting, NO\textsubscript{3}-N reduction followed first-order kinetics, and when carbon was not limiting, NO\textsubscript{3}-N reduction followed zero-order kinetics. The calculated first-order rate constants for the two soils studied were 0.815 and 0.520 per day for Crowley and Mhoon soil, respectively.

\[ \text{Crowley Silt Loam} \]

\[ \text{Mhoon Silt Loam} \]

![Graph of NH\textsubscript{4}-N and NO\textsubscript{3}-N concentrations](image)

Fig. 5—Relative rates of NH\textsubscript{4}-N oxidation and NO\textsubscript{3}-N reduction in the aerobic and anaerobic soil layers, respectively.
NO$_3$-N reduction usually occurred at a much faster rate than NH$_4$-N oxidation. Several other researchers have also shown that NO$_3$-N reduction rate constants for a number of soils ranged from 0.026 to 0.9 per day (Avnimelech, 1971; Bailey, 1976; Stanford et al., 1975; Reddy et al., 1980).

The four major processes described so far function simultaneously and continuously in flooded soils, shallow water bodies, lake bottoms, and possibly ocean mudds. In previous studies, Reddy et al. (1976), Patrick and Reddy (1976), Reddy and Patrick (1977) examined the overall effect of these processes in determining N loss from flooded soils. The present study was designed to examine each of the four processes in order to determine their relative rates. Our data show NH$_4$-N diffusion (0.059 to 0.216 cm$^2$/day) and NH$_4$-N oxidation (1.2 - 3.5 µg/g/day) function at slower rates than NO$_3$-N diffusion (0.96 - 1.94 cm$^2$/day) and NO$_3$-N reduction rates (0.315 - 0.520/day with half lives ranging from 1.3 - 2.2 days). Since NH$_4$-N oxidation and NO$_3$-N reduction rate constants have different units, the changes in the N (dc/dt) concentration as function of time were calculated for Crowley silt loam soil (Fig. 5). The calculated values indicate the rapid rate of NO$_3$-N reduction in the anaerobic layer compared with NH$_4$-N oxidation in the aerobic layer of flooded Crowley silt loam soil. Future research should be oriented to evaluate the significance of these processes in natural systems such as lake bottoms, coastal marshlands, and flooded fields.

LITERATURE CITED

ERRATA

Evaluation of Selected Processes Controlling Nitrogen Loss in Flooded Soil


Equation [7] on p. 1243 should read as follows:

\[ F = -D \int_0^t \frac{\partial C(0,t)}{\partial x} \, dt \]