Nitrate Movement Through the Soil Profile in Relation to Tillage System and Fertilizer Application Method

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Disciplines
Agriculture | Bioresource and Agricultural Engineering | Soil Science

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ABSTRACT

A n experiment was performed to determine the movement of NO₃-N through no-till and moldboard-plowed field plots. On the plowed plots, NO₃-N (about 150 kg/ha) was surface broadcasted either before or after tillage; on the no-till plots, only surface application of NO₃-N without tillage was used. Two rains of 12.7 and 6.35 cm (2.3 cm/h) were applied about one day apart with a rainfall simulator to the 5x5 m plots. Soil sampling down to 150 cm was performed before and after rainfall for soil water content and NO₃-N analyses.

Results showed that plots under no-till maintained significantly higher NO₃-N amounts in the 0- to 30-cm layer, with 40% of the NO₃-N initially present still there after 12.7 cm of rain and 33% remaining after the additional 6.35 cm of rain. The corresponding numbers for the moldboard-plow plots were 19 and 9%. The amount of NO₃-N leached from the 150-cm profile with 12.7 cm of rain was also less (29 kg/ha) for the no-till compared with moldboard-plowed plots (122 kg/ha).

INTRODUCTION

The use of chemicals in agriculture is recognized as a potential source of environmental pollution, specifically with respect to water quality. Nitrate-nitrogen (NO₃-N) pollution is one area that is currently receiving considerable attention. A certain portion of NO₃-N pollution comes from the use of agricultural fertilizers, which can wash directly from fields into streams and underground water sources. However, the extent of agricultural contributions of NO₃-N to both surface and subsurface waters is not fully known. Viets (1971) mentioned that circumstantial evidence indicates that water-quality deterioration could be associated with increased N-fertilizer use but positive evidence is not available.

Groundwater pollution is of increasing concern in the United States because about 50% of our drinking water comes from well water (Pye and Patrick, 1983). In the Midwest, NO₃-N pollution of drinking water supplies is being reported more and more frequently. Baker and Johnson (1981) reported that, in Iowa and elsewhere, NO₃-N concentrations in subsurface drainage from row-crop land usually exceed the 10 mg/L drinking water standard, and as fertilization increases, NO₃-N concentrations in tile drainage water sometimes approach 100 mg/L. A recent survey in Illinois reported that 81 percent of 221 dug wells and 34% of drilled wells in Washington county had a NO₃-N concentrations of more than 10 mg/L (Pye and Patrick, 1983). Also, Baker et al. (1985) found that about 25% of the 170 farm water-supply wells surveyed in one area of Iowa exceeded the NO₃-N standard of 10 mg/L.

Changing tillage practices in the Midwest are directly affecting the soil water properties of the surface soil and, thus, the leaching characteristics of soils. Tillage disturbs the macropores (open channels) in the upper 15 to 30 cm of the soil profile, whereas no-tillage allows developed macropores to persist. Rapid flow of water through macropores, as opposed to more homogeneous flow, may either increase or decrease the total movement of NO₃-N through the soil and to tile drains or underground water sources. The effects of surface connected macropores on NO₃-N transport in a tile-drained agricultural field have not been fully studied. One of the possible consequences resulting from water and NO₃-N movement through these macropores is that some of the NO₃-N in the surface layer of the soil may be moved to a much greater depth. Therefore, the time required for water to carry some of the NO₃-N to groundwater is not predicted by Darcian theory since assumptions of homogeneity of hydraulic properties of soil over some cross-sectional area will not be valid. However, the nonhomogeneous flow of water through macropores may mean less total leaching inasmuch as NO₃-N within soil aggregates may be bypassed.

A few researchers have attempted to look at the effects of tillage systems on the NO₃-N distributions in the soil profile (Juo and Lal, 1979; Kitur et al., 1984; Tyler and Thomas, 1977). Blevins et al. (1977, 1983) observed a rapid drop in soil pH in the surface soil (0-15 cm) under no-till conditions as compared to conventional tillage when 168 kg/ha of granular ammonium nitrate was surface broadcast, and soil pH decreased with increased level of N-fertilization. They found that as tillage is reduced, there is less mixing of applied amendments and crop residue into the soil. Thus, there is an accumulation of surface applied fertilizer in the surface soil. Tyler and Thomas (1977) found NO₃-N losses to be higher early in the growing season under no-till than under conventional tillage when nitrogen was surface broadcast as dry NH₄NO₃. They concluded that surface applied anions could be washed into natural soil cracks and channels...
and flow much deeper into the soil than predicted by miscible displacement. Bennett and Stanford* (1970, unpublished data) found considerably more \( \text{NO}_3^-\) in the top 120 cm of soil after corn harvest under no-tillage plots than under plowed plots, with most of the difference in the upper 60 cm of soil. A tentative explanation can be offered on the basis of the results reported by Power (1967, 1968) for the greater \( \text{NO}_3^-\) accumulation in the untilled plots. He found that greater amounts of N-fertilizer became incorporated in the soil organic matter under untilled plots than under plowed plots before the crop was planted, and in the second season, the amounts of mineral N were greater within no-till plots than within plowed plots.

Thomas et al. (1981) found that a common problem with nitrate under no tillage (granular \( \text{NH}_4\text{NO}_3\), applied as surface broadcast) is the possibility for substantial loss by leaching soon after planting and before the plants are large enough to remove significant nitrogen from the soil. Devitt et al. (1976) studied six different soil profiles and found that \( \text{NO}_3^-\) movement through the soil is affected by soil profile characteristics. Flow through macropores results in deeper penetration of surface-applied water and solutes than is predicted by uniform displacement (Beven and German, 1977; Scooter, 1978; Thomas and Phillips, 1979; Shuford et al., 1977; Warrick et al., 1971). Therefore, the link between flow through macropores as affected by tillage systems and the movement of surface applied nitrogen to tile drains or underground water needs to be studied under field conditions.

The objective of this research was to determine the effect of two tillage systems on the movement of \( \text{NO}_3^-\) in the soil profile in relation to rainfall and methods of N-fertilizer application (in solution form).

**EXPERIMENTAL PROCEDURE**

The experimental site was on a nearly uniform, flat Clarion-Nicollet loam soil at the Iowa State University Agronomy and Agricultural Engineering Research Center near Boone, Iowa. The study area had been used for row crops (corn-soybean rotation) under conservation tillage farming for the past five years (1979-1983). In 1979 and 1982, the experimental site was disked twice and in 1980 weeds were burned down with paraquat before seeding. This study was performed in August of 1983. Table 1 gives some of the pertinent properties of the Clarion-Nicollet-loam soil at the experimental site (Unlu, 1984; and USDA, 1984).

Twelve treatment plots 5x5 were laid out in a randomized block design with three replications, using two tillage practices (no-till and moldboard plowing) and two methods of N-fertilizer applications (surface-broadcast spray before or after tillage). For the no-till plots, surface incorporation of N-fertilizer was not possible; therefore, only the surface-broadcast method was used. Six plots were kept in no-till, and the remaining six were moldboard plowed (to 15 cm) followed by a pass of a tandem disk (to 8 cm) to level the plots. Out of six plots in no-till, three were used for collecting background soil samples and installing rain gauges; therefore, no fertilizer was applied on these plots. The background soil samples were used to determine the initial moisture contents and \( \text{NO}_3^-\) concentrations in the soil profile (before fertilization and rainfall simulation). Fig. 1 shows the layout of the experimental plots.

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**TABLE 1. PARTICLE SIZE, ORGANIC MATTER, TOTAL POROSITY, SATURATED HYDRAULIC CONDUCTIVITY, BULK DENSITY, AND VOLUMETRIC MOISTURE CONTENTS AT FIELD CAPACITY AND WILTING POINT OF CLARION-NICOLLET LOAM SOILS.**

<table>
<thead>
<tr>
<th>Depth cm</th>
<th>Particle size (in millimeters)</th>
<th>Organic matter</th>
<th>Saturated hydraulic conductivity</th>
<th>Porosity *</th>
<th>Bulk density g/cm³</th>
<th>Field capacity % vol.</th>
<th>Wilting point % vol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>sand 2-0.05</td>
<td>silt 0.05-0.002</td>
<td>clay &lt;0.002</td>
<td>cm/h 4.8</td>
<td>cm/h 0.90</td>
<td>44</td>
<td>35</td>
</tr>
<tr>
<td>15-30</td>
<td>42.9</td>
<td>29.4</td>
<td>27.7</td>
<td>3.7</td>
<td>2.61</td>
<td>49</td>
<td>1.35</td>
</tr>
<tr>
<td>30-45</td>
<td>44.8</td>
<td>28.1</td>
<td>27.1</td>
<td>2.2</td>
<td>2.58</td>
<td>46</td>
<td>1.38</td>
</tr>
<tr>
<td>45-60</td>
<td>46.9</td>
<td>27.8</td>
<td>25.3</td>
<td>1.7</td>
<td>2.46</td>
<td>46</td>
<td>1.42</td>
</tr>
<tr>
<td>60-90</td>
<td>44.8</td>
<td>31.1</td>
<td>24.1</td>
<td>0.7</td>
<td>2.39</td>
<td>45</td>
<td>1.55</td>
</tr>
<tr>
<td>90-120</td>
<td>48.1</td>
<td>34.4</td>
<td>20.5</td>
<td>0.3</td>
<td>2.10</td>
<td>43</td>
<td>1.65</td>
</tr>
<tr>
<td>120-150</td>
<td>49.6</td>
<td>33.5</td>
<td>16.8</td>
<td>0.1</td>
<td>2.10</td>
<td>42</td>
<td>1.72</td>
</tr>
</tbody>
</table>

*It is the volumetric moisture content (cm³/cm³) at saturation although total porosity of the soil may be slightly higher due to air entrapment in the soil profile.

†Bulk density of the plowed field tends to decrease sharply after plowing, but after heavy rains bulk densities of plowed fields were found to be close to the bulk densities of no-tilled fields. Therefore, same bulk densities were used for both no-till and plowed plots.

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*USDA-ARS, Morgantown, West Virginia.
Potassium nitrate (KNO$_3$) was applied in solution to the individual plots at the rate of about 150 kg NO$_3$-N/ha with a hand held sprayer, and 24-cm diameter filter papers, placed at two locations in each plot before fertilization, were used to determine the amount of fertilizer applied to each individual plot. The standard deviation for NO$_3$-N application over all the plots was 15.5 kg/ha. The filter papers were placed in areas about 1 m from later sampling sites (Fig. 2).

The rotating-boom rainfall simulator described by Swanson (1965), was used to apply a known amount of simulated rain at an average rate of about 2.3 cm/h on four 5x5 m plots at a time. The application rate of 2.3 cm/h was chosen after several trials to ensure that no surface runoff would occur from the experimental plots while simulated rainwater was being applied. Two simulated rains of 12.7 and 6.35 cm separated by about one day were applied to each plot. The first simulated rain of 12.7 cm was applied within 18 h of NO$_3$-N application. Before the first simulated rain, soil samples were taken to seven different depths of 15, 30, 45, 60, 90, 120, and 150 cm at six locations from the no-till plots with a hydraulic probe to get the information on the initial nitrate and soil water content of the soil profile. Each set of soil samples was removed in two cores with a probe 7.6 cm in diameter and 120 cm in length. Compaction of soil in the probe was slight and was seldom more than 3 cm. The cores were cut into the desired number of depth increments, and each soil sample was placed in a plastic bag and frozen for later laboratory analysis. The hydraulic probe was used only for taking soil samples before the application of simulated rainfall. After rainfall simulation, the soil samples were also taken to the same depths with smaller hand-driven probes 3.2 cm in diameter by either 31 or 46 cm in length, requiring up to five cores to be removed from the same hole to reach the 150 cm depth.

The first simulated rain of 12.7 cm (± 0.9 cm) was applied in about six hours (100 year 6-h duration storm) on four plots at a time (one of which had been used for background sampling). This large amount of simulated rain was chosen to enhance NO$_3$-N leaching and to test severe storm events. The next morning, soil samples were taken that created six 3.2 cm diameter holes in each plot. These holes were filled with nearby soil so that they would not act as large macropores when the next rain was applied. The second rain of 6.35 cm (± 0.6 cm) was applied in about three hours as soon as soil sampling was finished. A second set of soil samples were taken on the following or third day. Thus, each treatment plot received 19.05 cm of rainwater over a period of about 24 h (100 year 24-h duration storm) and 84 soil samples were taken from each treatment plot (42 after each rain), excluding background information plots. Fig. 2 gives the soil sampling network scheme. The sampling and rainfall events were staggered so that all three replications were completed in 125 h. There was no natural precipitation during this period.

Up to 300 g of each sample collected (in most cases all of the sample) was weighed into a preweighed 1000-mL beaker. Demineralized water (about 1.5 times the wet soil weight) was weighed into the beaker and the soil-water mixture was mechanically stirred for one hour. After settling, a small water sample for NO$_3$-N analysis was decanted. The remaining mixture was oven-dried overnight at 105°C and weighed. The gravimetric moisture contents of the original soil samples were calculated from the wet and dry weights; the conversion to volumetric moisture contents was made using the known depth-bulk density relationship (Table 1) for the soil in the experimental area. Analyses of water samples for NO$_3$-N were performed using the cadmium reduction method and a Technicon Auto Analyzer II$^+$ system. Concentrations in the soil solution were calculated from the analytical data, the weight of demineralized water added, and the soil water content.

RESULTS AND DISCUSSION

Effects of Tillage Systems on NO$_3$-N Movement

Figs. 3 and 4 show the average measured NO$_3$-N.

1Trade name is included for the benefit of the reader and does not imply endorsement or preferential treatment of the product by Iowa State University or the USDA.
concentrations in the soil profile after the application of 12.70 and a total of 19.05 cm of rainfall as a function of tillage systems and methods of N-fertilizer application. Also, these two figures give the least significant difference levels (LSD0.05) between the treatments as a function of soil depth. From Fig. 3 it is obvious that no-till plots had significantly greater NO₃-N concentrations near the soil surface (0-15 cm) in comparison with the moldboard-plowed plots. The relatively large NO₃-N concentration (221 mg/L) is very close to the NO₃-N concentration (224 mg/L) is very close to the NO₃-N concentration (221 mg/L) in the 0-15 cm layer from 221 mg/L to 160 mg/L.

A significantly lower NO₃-N concentration (42 mg/L) in the surface layer of moldboard plowed plots when NO₃-N was surface applied seems to indicate that upon plowing and disking, the soil aggregates became pulverized. This physical disturbance of the soil aggregates would also eliminate the large pores creating a more homogeneous system of smaller pores. This would expose more surface area to the water movement, thus allowing NO₃-N both residual and applied, to move more in accordance to the piston flow concept.

Table 2 gives the coefficient of variation in NO₃-N concentrations as a function of soil depth and treatment for the 18 soil cores taken (six per replication). From this table, the variability in NO₃-N concentrations can be estimated. It is clear from Table 2 that on the average large variations in NO₃-N concentrations are associated with the higher concentrations in the soil profile. Also, larger variations in NO₃-N concentrations are observed in the plowed plots in comparison with no-till plots.

Table 3 gives the mass balance of the total amount of NO₃-N found in the soil profile after 12.70 and 19.05 cm of simulated rain. The total nitrogen in the soil profile

<table>
<thead>
<tr>
<th>Soil depth, cm</th>
<th>Before rainfall</th>
<th>No-till, N-surface applied</th>
<th>Plow, N-surface applied</th>
<th>Plow, N-incorporated</th>
<th>LSD0.05 rainfall, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>229.6*</td>
<td>97.3</td>
<td>72.5</td>
<td>19.9</td>
<td>6.4</td>
</tr>
<tr>
<td>15-30</td>
<td>73.4</td>
<td>83.1</td>
<td>74.9</td>
<td>68.6</td>
<td>33.5</td>
</tr>
<tr>
<td>30-45</td>
<td>53.4</td>
<td>63.3</td>
<td>59.9</td>
<td>71.2</td>
<td>53.0</td>
</tr>
<tr>
<td>45-60</td>
<td>30.3</td>
<td>50.1</td>
<td>52.5</td>
<td>53.9</td>
<td>49.8</td>
</tr>
<tr>
<td>60-90</td>
<td>25.3</td>
<td>56.4</td>
<td>72.0</td>
<td>63.4</td>
<td>77.5</td>
</tr>
<tr>
<td>90-120</td>
<td>19.5</td>
<td>42.4</td>
<td>56.9</td>
<td>35.0</td>
<td>58.7</td>
</tr>
<tr>
<td>120-150</td>
<td>20.3</td>
<td>28.3</td>
<td>39.6</td>
<td>30.3</td>
<td>38.6</td>
</tr>
<tr>
<td>Total NO₃-N in the 0 to 150-cm depth</td>
<td>451.8</td>
<td>420.9</td>
<td>428.3</td>
<td>342.3</td>
<td>317.5</td>
</tr>
<tr>
<td>Net NO₃-N leaching loss below the 150-cm depth</td>
<td>28.9†</td>
<td>21.5†</td>
<td>121.5</td>
<td>146.3</td>
<td>44.2</td>
</tr>
</tbody>
</table>

*Includes an average of 151 kg/ha of applied NO₃-N (actually 149 ± 8 and 163 ± 11 kg/ha of NO₃-N was surface applied on no-till and moldboard plots respectively, and 140 ± 4 kg/ha of NO₃-N was surface incorporated on moldboard plots).
†That the data show an apparent small decrease in NO₃-N leaching with increased rain may be due to sampling and/or analytical errors (NO₃-N analyses are accurate to about ±5%).
comes from two indistinguishable sources of NO₃-N, residual nitrogen (initially present in the soil profile before N-application) and the applied NO₃-N. It shows that, after the surface application of an average of 149 kg/ha of NO₃-N on no-till plots and 12.70 cm of rain, 97 kg/ha of NO₃-N was found in the 0- to 15-cm layer (the initial nitrate content before fertilization was 78.6 kg/ha). This indicates that about 57% of the NO₃-N present at the start of the first rain (residual plus applied) had traveled from the 0- to 15-cm layer to the lower soil layers after 12.70 cm of rainfall under no-till conditions. For conventional tillage (plow + disk) plots, after the application of 163 kg/ha of N-fertilizer on the surface, the total NO₃-N found in the 0- to 15-cm layer was 19.9 kg/ha after 12.70 cm of rainfall. This shows that about 92% of the total NO₃-N present in the 0- to 15-cm layer was leached down to the lower soil layers after 12.70 cm of rainfall under conventional tillage. After application of 19.05 cm of rainfall, for no-till plots, 73 kg/ha of the NO₃-N was still in the 0- to 15-cm layer, but for conventional tillage plots, most of the NO₃-N had leached down from the 0- to 15-cm layer to the deeper soil profile (only 6 kg/ha of NO₃-N was present in the 0- to 15-cm layer).

Increases in NO₃-N concentrations and amounts were found below the 45-cm depth in both conventional tillage and no-till plots after the application of 12.70 cm of rain (Fig. 3 and Table 3). This implies that the bulk of the applied NO₃-N had moved to lower depths under both tillage systems as a result of leaching. Statistically, no significant difference was found in the amount of NO₃-N in the top 45 cm of soil profile between the two tillage systems after 12.70 cm of rainfall when NO₃-N was surface applied (Table 3 and Fig. 3). After an additional 6.35 cm of rainfall on the same plots (a total of 19.05 cm of rainfall), total NO₃-N increased considerably below the 60-cm depth under both tillage systems (Table 3). The nitrate concentrations at the 150-cm depth remained relatively constant and equal to the initial NO₃-N concentration after 12.70 cm of rain in both no-till and conventional plots (Fig. 3). A slight increase in the NO₃-N concentration was observed at the 150-cm depth after an additional 6.35 cm of rainfall under both tillage systems.

Fig. 5 gives the cumulative amounts of NO₃-N (residual and applied) in the soil profile as a function of tillage and simulated rain. This figure indicates that as the amount of simulated rain increased from 12.70 to 19.05 cm, NO₃-N was transported further down the soil profile. In no-till plots, 40% of the total NO₃-N present in the soil profile was found in the top 30 cm of the soil profile after 12.70 cm of rain (Table 4). It has frequently been assumed that 12.7 cm of continuously falling rain would leach a large amount of NO₃-N below the root zone portion of the soil profile. However, the findings of this study show that less than 6% of the total NO₃-N (initial plus applied) may have leached below the 150-cm after 12.70 cm of rain under no-till farming.

Under conventional tillage, NO₃-N leaching losses were much higher. After 12.70 cm of rain on moldboard plow plots with NO₃-N surface applied without incorporation, 26% of the total NO₃-N had leached past the 150 cm depth, and only 19% of the total NO₃-N was found in the top 30 cm of soil depth. After 6.35 cm of additional rain, 32% of the total NO₃-N was found to have been leached below 150 cm depth, and less than 9% was found present in the top 30 cm of the soil profile. This seems to indicate that, after large rains as tested in this study, the no-till system does a better job in retaining the NO₃-N within the root zone when compared with the moldboard plow tillage system.

Table 5 gives the soil water contents of the soil profile after 12.7 and 19.05 cm of rain and the least significant difference levels. This table shows that, before the application of the first rain, the soil average water content in the 150-cm soil profile was 39.9 cm (26.6% volumetric basis). After 12.7 cm of rain, the average volumetric soil water content in the 150-cm soil profile in the no-till plots increased to 33.5% and, in the conventional tillage plots, to 33.6%. The soil water contents increased to about 34.5% and 35.9% in no-till

![Fig. 5—Cumulative NO₃-N in the soil profile as a function of tillage, and simulated rain.](image-url)
and conventional tillage plots, respectively, after 19.05 cm of rain. Also, the data in Table 5 indicates that the average water contents in soil layers below the 60-cm depth were about 5% greater than in the soil layers in the top 60-cm after 12.70 and 19.05 cm of rainfall. This shows that additional rains could carry NO$_3$-N to deeper soil layers and eventually to the underground water sources.

**Effect of Method of N-fertilizer Application on NO$_3$-N Leaching**

Two methods of N-fertilizer application (surface broadcast and incorporation) were compared for NO$_3$-N movement under the moldboard plow treatment. Table 3 shows that relatively more NO$_3$-N moved down from the 0- to 30-cm layer after 12.70 cm of simulated rain in plots where N-fertilizer was surface incorporated. A possible explanation for this movement of NO$_3$-N in plots with incorporation of N-fertilizer is that the fertilizer had about a 10- to 15-cm head start due to inversion of the plow layer during incorporation. This helped to cause most of the NO$_3$-N (applied and residual) to travel to the deeper soil layers. This is also evident from Figs. 3 and 4 as NO$_3$-N peaks for both plowed treatments are separated by 15 cm.

Table 3 shows that after a total of 12.70 cm of rainfall, an average of about 121 kg/ha was found missing from the 150 cm soil profile from plots under conventional tillage with surface broadcast of N-fertilizer, which is unexplainably more than the 44 kg/ha for conventional tillage plots with surface incorporation of N-fertilizer. Most of the NO$_3$-N missing from the soil profile is believed to have leached below 150 cm depth as it is unlikely that denitrification of such large amounts of NO$_3$-N took place during the short period of the experiment. After an additional 6.35 cm of rainfall on the same plots, no statistically significant difference was found in the NO$_3$-N distribution in the soil profile under both methods of fertilizer application (Fig. 4 and Table 3).

**CONCLUSIONS**

Field experiments designed to determine the effects of tillage systems and methods of N-fertilizer application on NO$_3$-N movement through the soil profile resulted in the following conclusions for the conditions studied:

1. No-till plots retained significantly greater amounts of NO$_3$-N originally near the soil surface (residual plus applied in the 0-15 cm layer) in comparison to the moldboard-plowed plots after large rains. Also, under no-till conditions more NO$_3$-N was retained within the root zone (0-150 cm).

2. Higher NO$_3$-N leaching losses were observed in the moldboard plowed plots. For example, 26% of the total NO$_3$-N (residual plus applied) had moved below 150 cm depth in the moldboard plowed plots in comparison to only 6% in no-till plots after 12.70 cm of rain.

3. The effects of methods of fertilizer application on NO$_3$-N movement were not consistent. More NO$_3$-N was retained in the 0-30 cm layer for plots where NO$_3$-N was not incorporated, but more NO$_3$-N was missing from the 150 cm profile of these plots after 12.70 cm of rain.

**References**


