DIVISION S-10—WETLAND SOILS

Mineralization, Nitrification, and Denitrification in Histosols of Northern Minnesota

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ABSTRACT

Water content and temperature are influences on N mineralization, nitrification, and denitrification rates in drained Histosols. To look at possible differences in these rates and to enable comparisons to mineral soils, we collected soil samples from two Minnesota Histosols planted to cultivated wild rice (*Zizania palustris* L.), incubated amended subsamples at 4, 7, 10, 16, and 22°C, and monitored changes in NH_4 and plus NH_4-N with time. Amendments used were plus or minus NH_4 and plus or minus nitrapyrin. Net mineralization rates for Soil 1 (plus-nitrapyrin treatment) increased from 0.30 to 2.0 mg N kg^{-1} dry soil d^{-1} from 4 to 22°C. Nitrification and denitrification occurred simultaneously, with lower denitrification than nitrification rates. Nitrification rates determined from the zero-order plots of the disappearance of NH_4-N with time in the plus-NH_4 samples) increased from 4 to 22°C (Soil 1, 17–99 mg N kg^{-1} d^{-1}; Soil 2, 11–40 mg N kg^{-1} d^{-1}). Soil 1 nitrified faster than most mineral soils; Soil 2 was comparable with many mineral soils. Denitrification rates for Soil 1, determined from the decrease in total inorganic N (NH_4-N + NO_3-N; plus-NH_4 samples), increased from 9 mg N kg^{-1} d^{-1} at 4°C to 53 mg N kg^{-1} d^{-1} at 22°C. There were no differences between the two experimental water contents (corresponding to soil water pressure heads of −25 and −50 cm) for any of these rates. The high water-holding capacity of Histosols increases the potential for simultaneous nitrification and denitrification and will result in removal of native and applied NH_4 from the system, thus affecting N use efficiency of both wild rice and upland crops grown on Histosols.

THE FATE of NH_4–N added to soil by fertilizer or by mineralization of organic N is important for agricultural production on Histosols. In drained soils, NH_4 is converted to NO_3. Nitrate can then be lost by leaching, by denitrification in anaerobic microsites (Tiedje, 1988; Paul and Clark, 1989), or by denitrification if the soils are subsequently flooded for production of a paddy crop (Ponnamperuma, 1972; Patrick and Reddy, 1978). In Minnesota, Histosols are used both for production of upland crops and for paddy-grown wild rice, an aquatic grass native to north-central North America. Paddies were developed as part of an effort to reduce the extreme fluctuations in grain production common in natural stands that limited the development of a market for the grain. As part of this effort to domesticate wild rice, research into N use by wild rice was undertaken to improve efficiency and lower production costs (Elder, 1981; Grava et al., 1985; Meyer et al., 1989; Zanner and Bloom, 1990).

Fifty to eighty percent of the N needed by a wild rice crop is mineralized under flooded conditions during the growing season (Bloom and Meyer, 1988; Meyer et al., 1989). This agrees with research on white rice (*Oryza sativa* L.) by DeDatta (1981) and Broadbent (1978), who estimated that fertilized white rice obtains 50 to 80% of its N requirement from mineralization. The remainder of the required N is supplied by fertilization and by mineralization during the unflooded portion of the year (under aerobic conditions). However, to be available for crop growth, mineralized N and fertilizer N must persist in the soil until needed by the crop. The findings of Bloom and Meyer (1988), which showed erratic response of wild rice even to high added rates of fall-applied N, lead us to suggest that both fertilizer N and mineralized N were being lost from the soil.

In upland settings, nitrification of NH_4 may lead to leaching when excess moisture is present. Leaching of NO_3 is not a major concern in Minnesota wild rice paddies because they are developed in low areas near the water table; however, nitrification is of particular interest in soils used for the production of wild rice because conversion of fall-applied NH_4 to NO_3 can result in N loss during spring flooding. Any NO_3 present in soil is rapidly denitrified once available O_2 is consumed during the first few days after flooding (Ponnamperuma, 1972; Patrick and Reddy, 1978), and thus is not available for plant uptake. Information about nitrification rates would thus be important for estimating N loss due to leaching and denitrification.

The high water-holding capacity and pore structure of Histosols allow for rapid air exchange in large pores concurrently with intraaggregate anaerobiosis. High but less than saturated bulk soil water content can lead to denitrification within aggregates. Knowledge of denitrification rates is important for understanding the fate of N and thus would be of interest in interpreting N use by all types of crops grown on drained Histosols.

Wild rice paddies are flooded in early spring and then drained in late summer for harvest. Field work is limited to the fall because it is not practical to apply fertilizer to partially frozen ground just before spring flooding. As a consequence, fertilizer is applied when it will be influenced by aerobic conditions. Timing of fall application of NH_4 forms of fertilizer is thus important if nitrification is to be minimized. On mineral soil, Keeney (1982), Gomes and Loynachan (1984), Tisdale et al. (1985), and Rehm (1988) are among many who recommend that N be applied when the soil temperature is $\leq 10°C$ (50°F) to minimize the transformation of NH_4 to NO_3 and the subsequent loss of NO_3 by leaching.

Erratic response to fall-applied N in wild rice suggests

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Abbreviation: TIN, total inorganic nitrogen.

that losses due to nitrification in the fall and subsequent denitrification during spring flooding may be great. However, no data are available for mineralization and nitrification rates for Histosols under the typical conditions that follow fall fertilization of wild rice paddies. Information is limited concerning potential denitrification of nitrified N in anaerobic microsites of an otherwise aerobic Histosol, which may be important in determining N availability to all crops grown on these soils. The objective of this study was to determine potential mineralization, nitrification, and denitrification rates for organic soils from north-central Minnesota as affected by soil water content and temperature.

MATERIALS AND METHODS

Soil Collection and Preparation

Soils were collected in the fall of 1990 from Minnesota wild rice paddies in Aitkin County (Soil 1) and Clearwater County (Soil 2). The soils are representative of the areas where wild rice is grown. Plant residue was removed from the soil as it was sampled and during sieving of field-moist soil in the laboratory with a 3-mm-mesh sieve. Soils were sealed in plastic buckets and stored at 4°C. Table 1 lists selected properties for both soils; additional information was presented by Zanner (1992).

Soil Water Content

The two field-moist soils were dried in triplicate at 65°C (Day et al., 1979) until consecutive weighings changed by <0.03% to determine their initial water content. Throughout the experiment, any weights were adjusted to oven-dry weights using the average initial water content for each soil. Water retention curves for the two soils in the range of 0 to −100 cm of soil water pressure head were developed using a modified version of the method of Berliner et al. (1980; data not shown; for details, see Zanner, 1992.) The modification utilized a Mariotte-bottle substitute (250-mL side-arm flask, rubber tubing, and pipette tip). The water contents corresponding to −25 and −50 cm heads used for this experiment are in the range found for drained Histosols where drainage tiles are at a depth of 75 to 100 cm. As determined from the water retention curves, a soil water pressure head of −25 cm corresponds to a soil water content of 0.73 kg kg^{-1} moist soil for Soil 1 and 0.765 kg kg^{-1} moist soil for Soil 2. A head of −50 cm corresponds to 0.71 kg kg^{-1} moist soil for Soil 1 and 0.755 kg kg^{-1} moist soil for Soil 2 (Zanner, 1992). The pore structure of these Histosols resulted in a large change in soil water content in the first few centimeters of change in head, followed by very slow changes in soil water content as the pressure head decreased.

Table 1. Selected properties for soils collected from wild rice paddies in Aitkin County, Minnesota (Soil 1) and Clearwater County, Minnesota (Soil 2) and subsequently used in N transformation incubations.

	Soil 1	Soil 2
Classification	Borosaprist	Borosaprist
pH (field moist soil; ≈2.5:1 H_2O)	6.7	7.1
Ash content (kg kg^{-1})	0.382	0.432
Bulk density (Mg m^{-3})	0.20	0.24
Total N (kg kg^{-1})	0.019	0.021
C/N	17:1	12:1
2 *M* KCl extractable NH_4 (g kg^{-1} dry soil)	41.5	29.1
2 *M* KCl extractable NO_3 (g kg^{-1} dry soil)	2.6	6.9

Treatments

Ammonium chloride was added as the NH_4 source at a rate of 380 mg kg^{-1} of dry soil, equivalent to 114 kg N ha^{-1} for a 15-cm plow layer, which would be a high but not abnormal field rate. Nitrapyrin was used to inhibit nitrification at a rate of 190 mg a. i. kg^{-1} of dry soil.

Nitrapyrin and NH_4 were added gravimetrically to small amounts of soil with spray bottles. The soils were kept in an ice bath to minimize microbial growth during treatment. Two grams of treated soil (dry-weight basis) were placed into 50-mL polyethylene centrifuge tubes and wetted to the desired gravimetric water content. Approximate field bulk density was achieved by tapping the tubes on a laboratory bench until each soil sample occupied the appropriate volume for the sample weight and field bulk density. The tubes were loosely capped, then placed in covered plastic buckets with two uncovered beakers of water to maintain high humidity and to limit evaporation. Buckets were placed in five incubators, each of which had been set at the appropriate temperature and monitored for temperature stability (±1°C) before the start of the experiment. Table 2 summarizes the experimental conditions.

Analyses

At time zero and at each of seven sample collection dates, tubes were removed from the buckets and the soil was extracted with 30 mL of 2 *M* KCl directly in the incubation tubes. Remaining tubes were checked for weight loss, and water was added as needed. We used a collection schedule that differed for each incubation temperature to capture the presumed increase in rates of change of NH_4 to NO_3 typically found with increasing temperatures. After 30 min on a reciprocating shaker, samples were filtered and the filtrate was stored at 2°C until analyzed. Analysis for NH_4–N and NO_3–N concentrations was performed on an Alpkem RFA-300 Autoanalyzer (Alpkem Corp., Clackamas OR). Ammonium-N concentration was determined colorimetrically by the indophenol blue method (Alpkem, 1987); NO_3–N concentration was determined after reduction to NO_2 by Cd metal by the sulfanilimide diazotization method (Alpkem, 1986).

Mineralization, nitrification, and denitrification rates were determined from plots of time vs. NH_4–N and NO_3–N concentrations where appropriate (Table 3). Plots were examined to determine if there were linear phases of mineralization, nitrification, or denitrification. Mineralization rates at each temperature were determined on the $-NH_4$, +nitrapyrin treatments from the slope of the plots of NH_4–N concentration vs.

Table 2. Summary of experimental conditions. Subsamples of each Histosol were treated with one of the indicated amendments, adjusted to one of the two soil water contents, and incubated at one of the indicated temperatures so as to produce all soil × amendment × head × temperature combinations.

Soils	Soil 1 (from Aitkin County); Soil 2 (from Clearwater County)
Amendments	$-NH_4$, −nitrapyrin; $-NH_4$, +nitrapyrin; $+NH_4$, −nitrapyrin; $+NH_4$, +nitrapyrin
Amendment rate	NH_4 added at 380 mg N kg^{-1} dry soil; nitrapyrin added at 190 mg kg^{-1} dry soil
Soil water pressure head	−25 and −50 cm
Soil water content	Soil 1, 0.73 and 0.71 kg kg^{-1} moist soil; Soil 2, 0.765 and 0.755 kg kg^{-1} moist soil
Temperature, °C	4, 7, 10, 16, 22
Subsamples collected	16 at time zero plus 80 treatment combinations sampled seven times each; total 576

time. Mineralization rates determined here are net rates, the difference between rates of N mineralization and immobilization. Without ^{15}N, it is not possible to determine separate mineralization and immobilization rates. Nitrification rate curves in mineral soils are generally sigmoidal, with a delay phase resulting from bacterial growth adjustment to new environmental conditions, a zero-order phase representing the maximum rate of NH_4 disappearance, and a retarded phase as NH_4 becomes limiting for nitrification (Sabey et al., 1959, 1969; Hadas et al., 1986; Laubscher et al., 1990). Nitrification rates were obtained from the linear portion of the rates of disappearance of NH_4-N in the $+NH_4$, $-$nitrapyrin treatments. Similarly, denitrification rates were determined by summing the difference between initial total inorganic N (TIN = NH_4-N plus NO_3-N concentrations) and TIN at each measurement time, then determining rates of change at each temperature from the plots of TIN vs. time. These nitrification and denitrification rates are influenced by NH_4 mineralized in excess of immobilization but mineralization rates are low compared with nitrification and denitrification rates. The increase in the rate of each process with a 10°C increase in temperature (i.e., Q_{10}) was determined from plots of $1/T$ (K) vs. rate.

Results were analyzed to look for significant differences in rates among all amendment × soil water × temperature interactions for each soil using Microsoft Excel 4.0 (Microsoft Corporation, 1992–1994), the statistical package Systat (Wilkinson et al., 1992), and a test for homogeneity of regression coefficients according to Gomez and Gomez (1984). Slope regression coefficients were analyzed to determine if we could reject the hypothesis that the slopes of the linear portions were homogeneous. If not, the slopes were further analyzed to see if there were significant differences among the five slopes for any amendment × soil water × temperature interaction (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Effect of Water Content and Soil Type

Results of the nitrification experiments are shown in Fig. 1 for Soil 1. The rate of NH_4-N disappearance from the $+NH_4$, $-$nitrapyrin treatment was similar for the two soil water contents. Soil 1 is shown in Fig. 1; similar results were found for Soil 2. All statistical analyses were thus performed after combining the data for water contents corresponding to -25 and -50 cm soil water pressure head. Sufficient O_2 was available for rapid nitrification even under these conditions when the soils retained significant amounts of water. In Histosols, nitrification should proceed if there is adequate drainage, even when the water content of the soil is high. Campbell et al. (1981) found that subsurface drainage tile placed at ≈1.2 m will aerate a Histosol to a depth of 1 m.

Ammonium-N loss from Soil 1 for the $+NH_4$, $-$nitrapyrin treatment began sooner and was consistently faster than in Soil 2 (Fig. 2) in all treatments and at all temperatures. This may have been due to differences in the field operations that had been completed at the time of sampling. Both soils were collected after harvest, but Soil 2 was collected before chopping and incorporation of wild rice stalk and leaf residue, while Soil 1 was collected after these operations. Chopping and incorporation of surface plant residue should have increased the

Table 3. Methods used to determine rates of mineralization, nitrification, and denitrification from an incubation study of two Histosols collected from wild rice paddies in Aitkin County, Minnesota, and Clearwater County, Minnesota.

1. Mineralization: Subsamples with treatment $-NH_4$, + nitrapyrin were analyzed for changes in NH_4-N concentration with time at each incubation temperature. The linear portion of the plot of NH_4-N concentration vs. time was identified. The slope of this portion represents the net mineralization rate.
2. Nitrification: Subsamples with treatment $+NH_4$, $-$nitrapyrin were analyzed for changes in NH_4-N concentration with time at each incubation temperature. The linear portion of the plot of NH_4-N concentration vs. time was identified. The inverse of the slope of this portion represents the rate of nitrification.
3. Denitrification: Subsamples with treatment $+NH_4$, $-$nitrapyrin were analyzed for changes in NH_4-N and NO_3-N concentrations with time at each incubation temperature: NH_4-N + NO_3-N concentrations = total inorganic N (TIN). A decrease in TIN between time t and time $t + 1$ represents the quantity of N lost due to denitrification. The linear portion of the plot of TIN vs. time was identified. The slope of this portion represents the denitrification rate.

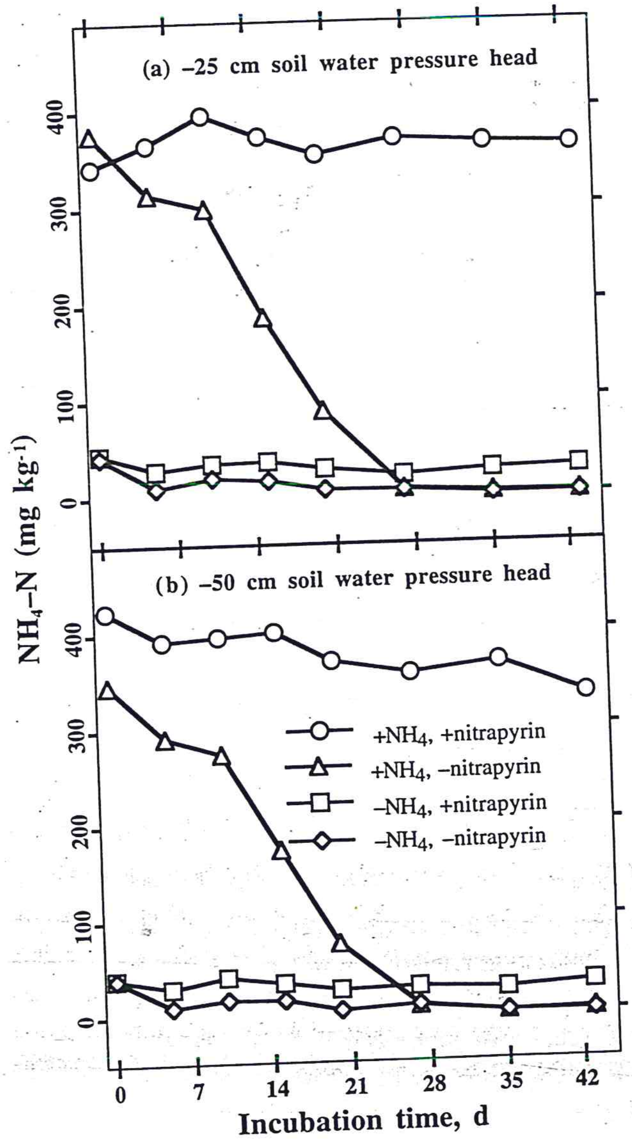

Fig. 1. Influence of four experimental treatments on changes in NH_4-N concentration in a Histosol collected from a wild rice paddy in Aitkin County, Minnesota (Soil 1). This set of treatments was incubated at 4°C and at water contents corresponding to soil water pressure heads of (a) -25 cm and (b) -50 cm.

Table 4. Rates of mineralization, nitrification, and denitrification from an incubation study of two Histosols collected from wild rice paddies in Aitkin County, Minnesota (Soil 1) and Clearwater County, Minnesota (Soil 2) including net N mineralization and denitrification rates for Soil 1 and nitrification rates for both soils. Mineralization rates were determined from the slope of the plots of the increase in NH_4-N concentration with time in the $-NH_4$, +nitrapyrin treatment. Nitrification rates were determined from the slope of the plots of the decrease in NH_4-N concentration with time in the $+NH_4$, −nitrapyrin treatment. Denitrification rates were determined from the slope of the plot of the decrease in total inorganic N (TIN; NH_4-N + NO_3-N concentrations) with time in the $+NH_4$, −nitrapyrin treatment. (The r^2 values of the plots ranged from 0.88 to 1.0.)

Temperature	Mineralization rate, Soil 1	Nitrification rate		Denitrification rate, Soil 1
		Soil 1	Soil 2	
°C	— mg N kg^{-1} dry soil d^{-1} —			mg TIN kg^{-1} dry soil d^{-1}
22	2.0a†	99a	40a	53a
16	1.5a	63b	25a	33b
10	0.51b	32c	15b	18c
7	0.49b	21d	12b	10d
4	0.30b	17e	11b	9d

† Letters after each value within a column indicate rates significantly different from each other, determined by testing for homogeneity of regression coefficients using the methods of Gomez and Gomez (1984), $P < 0.05$.

available O_2, should have increased the quantity of readily decomposable plant material, and would have incorporated surface soil with a high aerobe population, thus priming the soil for mineralization and nitrification.

Net Nitrogen Mineralization

Nitrapyrin was effective in limiting nitrification (Fig. 1), and this inhibition of nitrification enabled us to determine mineralization rates. After initially decreasing, NH_4-N concentration in the $-NH_4$, +nitrapyrin treatment increased linearly with time for Soil 1. Net mineralization rates for Soil 1 (Table 4) ranged from 0.30 mg N kg^{-1} d^{-1} at 4°C to 2.0 mg N kg^{-1} d^{-1} at 22°C. In Soil 2, NH_4-N concentration did not show a linear increase until the last few data points, and this prevented a meaningful interpretation of the results.

Other investigators of Histosols have reported comparable mineralization values. From the data of Terry (1980) for Florida Histosol samples to 75-cm depths at 25°C and −333 cm head, we calculated rates of 1.4 to 2.0 mg N kg^{-1} d^{-1} (assuming a bulk density of 0.25 Mg m^{-3}). Terry (1980) also reported that cropped Histosols have higher mineralization rates than uncropped Histosols. Using intact soil columns (70 cm long) from Florida that were incubated for 53 wk at a head of −100 cm and ambient temperatures, Reddy (1982) found mineralization rates of 0.6 to 1.5 mg N kg^{-1} d^{-1}. Our rates are greater than those obtained by Isirimah and Keeney (1973), who reported an average mineralization rate for nine Wisconsin Histosols at 30°C that we calculated to be 0.4 mg N kg^{-1} d^{-1} (assuming a bulk density of 0.25 Mg m^{-3}). However, these researchers did not recognize the potential for denitrification in their aerobic samples, although they did note that N was being lost from the system, and the true mineralization rates were thus higher.

Mineralization rates of Soil 1 increased by a factor of 3.0 with a 10°C temperature increase (r^2 = 0.95, P = 0.0044; plot not shown). The increase in the rate of biological activity with a 10°C increase in temperature is defined as the Q_{10}. This Q_{10} of 3.0 compares with Q_{10} values of 2.3 between 5 and 15°C for 11 mineral soils, decreasing to Q_{10} = 2 between 15 and 25°C (Stanford et al., 1973). Reddy (1982) reported mineralization Q_{10} values of 1.9 for four cultivated organic soils and 1.5 for two virgin organic soils in Florida.

Bloom and Meyer (1988) estimated the annual N requirement for wild rice to be 90 kg N ha^{-1}; Grava and Raisanen (1978) estimated the requirement to be 120 kg N ha^{-1}. Mineralization rates based on our incubation would result in N mineralization in the rooting zone of wild rice (the top 0.50 m) after harvest of 0.23 kg ha^{-1} d^{-1} at 4°C to 1.6 kg ha^{-1} d^{-1} at 22°C. Between harvest and freeze-up, mineralization could thus add 15 to 20 kg of N even at the lowest rate, a substantial portion of the N requirement for wild rice if N remained in the NH_4 form and was not lost by nitrification and denitrification.

Nitrification and Denitrification

Nitrification rates, indicated by the rate of disappearance of NH_4-N in the $+NH_4$, −nitrapyrin treatment, increased with increasing temperature for both soils (Fig. 2, Table 4). At all temperatures, Soil 1 reacted more quickly than Soil 2. Disappearance of NH_4-N with time was similar to that observed by Sabey et al. (1959, 1969), Hadas et al. (1986), and Laubscher et al. (1990) for nitrification in mineral soils.

The Q_{10} for nitrification was estimated to be 2.9 (r^2 = 0.99, P = 0.0003) for Soil 1 and 2.1 (r^2 = 0.97, P = 0.0024) for Soil 2 (plots not shown). These values are comparable with estimates for nitrification in mineral soils. Sabey et al. (1959) reported Q_{10} values of ≈2 to 5 for various soil types under different agricultural management. Tyler et al. (1959) found an average Q_{10} of 2.1 for four soils (sandy loam, loam, and two clays), with a range from 1.6 to 3.3.

Nitrification rates are not available for cultivated organic soils. Those for mineral soils vary widely; however, the reported rates (Sabey et al., 1959; Tyler et al., 1959; Brandt et al., 1964; Mahli and McGill, 1982; Hadas et al., 1986; Nishio and Fujimoto, 1990) bracket the rates we found in our Histosols. In incubations performed under a variety of conditions (7–35°C; 0–800 mg N added kg^{-1} dry soil; water content near field capacity), nitrification rates ranged from 1 to 130 mg N kg^{-1} d^{-1}, with all but Sabey et al. (1959) reporting values at or below 70 mg N kg^{-1} d^{-1}. At 22°C, our rate in Soil 1 is in the high end of the range, and our rate in Soil 2 is comparable with these mineral soils (Table 4).

Nitrification and denitrification occurred simultaneously in Soil 1 and Soil 2 (Fig. 3). Nitrate reached a maximum value of ≈150 mg NO_3-N kg^{-1} at all temperatures and maintained this concentration as NH_4-N disappeared (Fig. 3A). This suggested that NO_3 was being removed by denitrification. Simultaneous occurrence of nitrification and denitrification in this system indicated

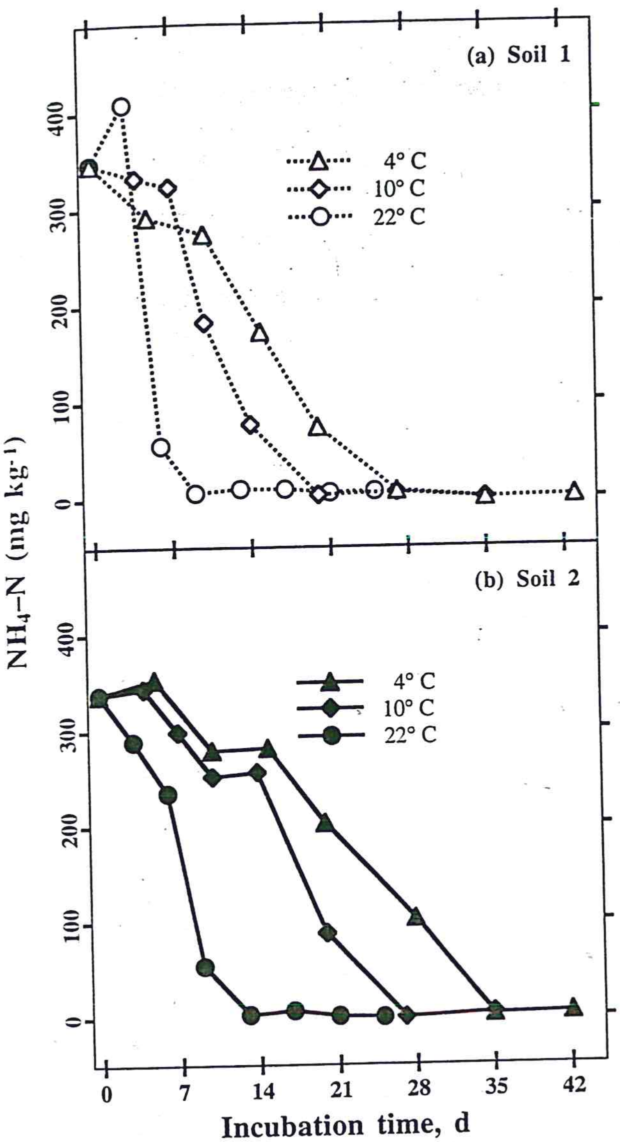

Fig. 2. Influence of temperature on rates of NH_4-N concentration decrease in the $+NH_4$, −nitrapyrin treatment of two Histosols collected from wild rice paddies in (a) Aitkin County, Minnesota (Soil 1) and (b) Clearwater County, Minnesota (Soil 2), and incubated at a water content corresponding to −50 cm soil water pressure head at 4, 10, and 22°C.

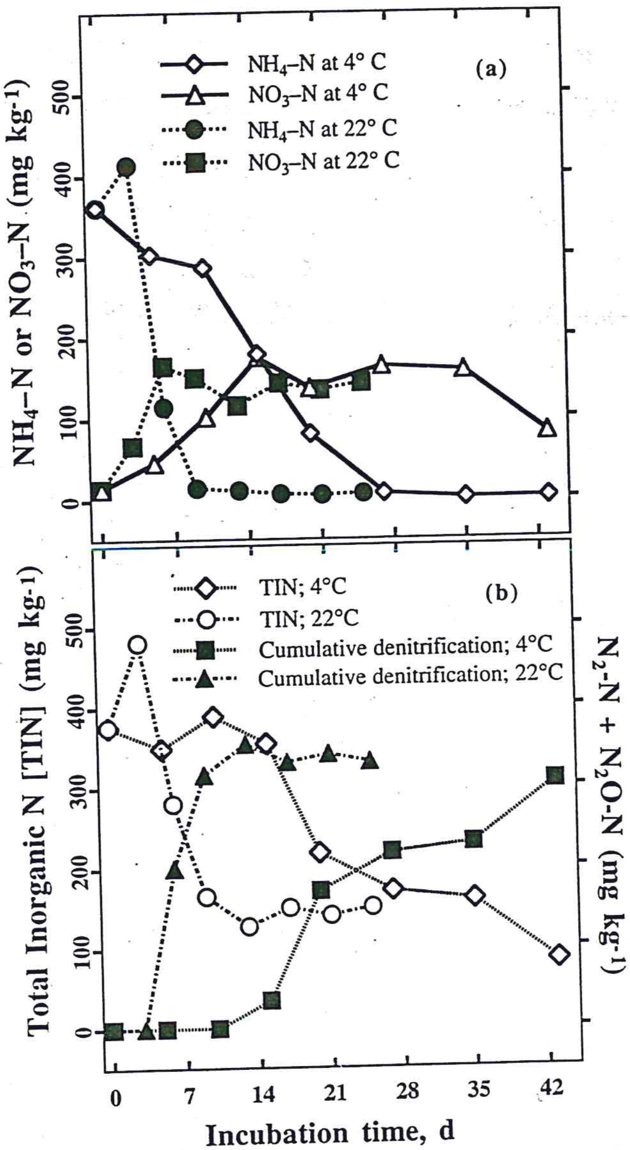

Fig. 3. Changes in (a) NH_4-N and NO_3-N concentrations with time in a Histosol collected from a wild rice paddy in Aitkin County, Minnesota (Soil 1), $+NH_4$, −nitrapyrin treatment, at 4 and 22°C; and (b) total inorganic N (TIN, = NH_4-N + NO_3-N concentrations) and denitrified N (N_2-N + N_2O-N) with time. Denitrified N is determined by assuming that any decrease in TIN between time t and time $t+1$ represents N lost by denitrification. Thus $[N_2\text{-N} + N_2O\text{-N}]_{Total} = \Sigma\{[NH_4\text{-N} + NO_3\text{-N}]_t - [NH_4\text{-N} + NO_3\text{-N}]_{t+1}\}$.

that both aerobic and anaerobic sites were present. This is common in soils (Tiedje, 1988; Paul and Clark, 1989). According to Harris (1981), water-saturated soil crumbs >3 mm in radius have O_2-free centers. The high water-holding capacity of Histosols would tend to result in many anaerobic microsites.

Estimates of rates for denitrification were obtained from the linear portion of the plots of the increase in cumulative denitrification with time (Table 4; Fig. 3b shows 4 and 22°C). Our maximum rate (53 mg kg^{-1} d^{-1} at 22°C, obtained for Soil 1) compares with a maximum potential rate for flooded Histosols at 30°C of 110 mg kg^{-1} d^{-1} as determined by Terry and Tate (1980). The Q_{10} for denitrification in Soil 1 was 2.9 ($r^2 = 0.98$, $P = 0.0015$, plot not shown). Although the absolute rates for denitrification in Soil 1 were lower than nitrification rates, Q_{10} for denitrification was very similar to the Q_{10} for nitrification. As was the case for mineralization of NH_4-N in Soil 2, TIN (NH_4-N + NO_3-N concentrations) did not show a linear change until the last few data points, and this prevented a meaningful interpretation of the results.

Both nitrification and denitrification were rapid and increased with increasing temperature (Fig. 3). This pattern was similar for both soils, with the processes more rapid in Soil 1 than in Soil 2. Rates of denitrification were slower than rates of nitrification, as is expected, because denitrification is limited by the rate of formation of NO_3 and by the rate of diffusion of NO_3 into anaerobic microsites (Myrold and Tiedje, 1985). These researchers found that C supply can also limit denitrification, but C should not limit denitrification in Histosols. Persistence of NO_3 until NH_4 was no longer available for nitrification (Fig. 3) indicated that some portion of the samples was oxygenated enough to limit denitrification.

Others have shown denitrification is significant at low temperatures in temperate regions. Cho et al. (1979) estimated that 2.7°C was the threshold temperature for denitrification in three irrigated soils from Alberta, Canada. Unlike mineral soil where denitrifier activity tends to be concentrated in surface horizons, activity is maintained in Histosols to deeper depths. Indeed, Khan and Moore (1968) found active denitrifier populations to 101 cm in a mineral horizon below a Histosol.

Soil temperatures at depths of 20 and 40 cm were monitored at the Soil 1 sampling site through the fall of 1990 (Zanner, 1992). Soil temperatures in mid-October were still near 10°C. Denitrification following nitrification would represent a field loss rate in Soil 1 of 6.8 kg N ha^{-1} d^{-1} at 4°C and 12.8 kg N ha^{-1} d^{-1} at 10°C (soil bulk density of 0.20 Mg m^{-3} and assuming a plow layer of 20 cm). In Soil 2, the loss rate would be 4.4 kg N ha^{-1} d^{-1} at 4°C and 6.0 kg N ha^{-1} d^{-1} at 10°C (soil bulk density of 0.24 Mg m^{-3} and assuming a plow layer of 20 cm). The potential for high losses of N during fall fertilizer applications caused by nitrification and subsequent denitrification is thus a major concern. As Zanner (1992) noted, erratic field results from fertilizer trials (Grava and Raisanen, 1978; Bloom and Meyer, 1988) suggest that nitrification and denitrification result in the loss of fertilizer and mineralized N. Nitrification of NH_4–N is not only a concern for wild rice farmers who will later flood their fields but also is a concern for growers of upland crops because of the high potential for simultaneous nitrification–denitrification.

CONCLUSIONS

Net N-mineralization rates obtained in this study ranged from 0.30 mg N kg^{-1} d^{-1} at 4°C to 2.0 mg N kg^{-1} d^{-1} at 22°C. This suggested that post-harvest mineralization was capable of supplying a significant portion of the N requirement to the following crop. Actual N availability would depend on persistence of NH_4–N in the soil.

These two organic soils from Minnesota nitrified at rates that indicated that the potential for nitrification of fall fertilizer and mineralized NH_4 is rapid even at temperatures below 10°C. Application of NH_4 fertilizer when soil is below this temperature will still produce yield-affecting losses when denitrification follows. Nitrapyrin was effective in inhibiting nitrification at all temperatures, indicating that it could be useful in the development of methods to minimize nitrification in Histosols.

Denitrification rates were lower than the rates for nitrification in each soil, and denitrification continued at very low soil temperatures. Denitrification in organic soils will continue late into the fall in northern temperate regions where subsoils are well insulated by organic surface horizons.

It is well recognized in flooded agricultural systems that denitrification will occur on flooding and that this represents a loss of plant-available N. It is not so obvious that substantial denitrification can occur in Histosols under what are assumed to be aerobic conditions due to the presence of anaerobic sites within soil peds. The high water-holding capacity of organic soils will increase the potential for simultaneous nitrification and denitrification and will result in removal of available N from the system. This means that nitrification followed by denitrification can result in losses for upland crops even without flooding, and these linked processes must be considered in determining the fate of mineralized and applied N in Histosols.

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