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# Mineralization and denitrification in upland, nearly saturated and flooded subtropical soil

## II. Effect of organic manures varying in N content and C:N ratio

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**Abstract** Nitrogen and carbon mineralization of cattle manure ($N=6$ g kg$^{-1}$; $C:N=35$), pressmud ($N=17.4$ g kg$^{-1}$; $C:N=22$), green manure ($N=26.8$ g kg$^{-1}$; $C:N=14$) and poultry manure ($N=19.5$ g kg$^{-1}$; $C:N=12$) and their influence on gaseous N losses via denitrification (using the acetylene inhibition technique) in a semiarid subtropical soil (Typic Ustochrepts) were investigated in a growth chamber simulating upland, nearly saturated, and flooded conditions. Mineralization of N started quickly in all manures, except pressmud where immobilization of soil mineral N was observed for an initial 4 days. Accumulation of mineral N in upland soil plus denitrified N revealed that mineralization of cattle manure-, pressmud-, poultry manure- and green manure-N over 16 days was 12, 20, 29 and 44%, respectively, and was inversely related to C:N ratio ($R^2=0.703$, $P=0.05$) and directly to N content of organic manure ($R^2=0.964$, $P=0.01$). Manure-C mineralized over 16 days ranged from 6% to 50% in different manures added to soil under different moisture regimes and was, in general, inversely related to initial C:N ratio of manure ($R^2=0.690$, $P=0.05$). Cumulative denitrification losses over 16 days in control soils (without manure) under upland, nearly saturated, and flooded conditions were 5, 23, and 24 mg N kg$^{-1}$, respectively. Incorporation of manures enhanced denitrification losses by 60-82% in upland, 52–163% in nearly saturated, and 26–107% in flooded soil conditions over a 16-day period, demonstrating that mineralized N and C from added manures could result in 2- to 3-fold higher rate of denitrification. Cumulative denitrification losses were maximal with green manure, followed by poultry manure, pressmud and cattle manure showing an increase in denitrification with increasing N content and decreasing C:N ratio of manure. Manure-amended nearly saturated soils supported 14–35% greater denitrification than flooded soils due to greater mineralization and supply of C.

**Key words** Denitrification · N mineralization · Semiarid subtropical soils · Flooded rice systems · Water regime

## Introduction

To maintain soil productivity and supply plant nutrients, farm and city wastes have been used from ancient times. However, in order to meet the ever-increasing needs for food and fiber for growing populations, especially in Asia and other tropical and subtropical regions, and with introduction of high-yielding crop varieties during the 1970s and 1980s, the use of organic sources declined while that of chemical fertilizers increased (De Datta and Buresh 1989). This shift was mainly due to high availability of inorganic fertilizers and low N yield potential of organic manures to meet the nutritional requirement of high-yielding cultivars (Singh 1984; Yadvinder-Singh et al. 1991). On a global basis it has been established that manufacturing of N fertilizer alone accounts for about one third of the energy consumed in agriculture (McCune 1984). To reduce dependence on non-renewable energy sources, decrease the fertilizer cost in farming, and maintain fertility and productivity of soils, renewed emphasis is being laid on the use of organic sources (Meelu and Morris 1987; Nagarajah 1988; Singh et al. 1991; Aulakh et al. 1999a). Farm-borne organic materials are available in abundance in Asia. For instance, India has highest cattle population in the world. Poultry production is one of the main systems in densely populated South and Southeast Asian countries. Green manure is pro-

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duced on farm by growing short duration fast N-accumulating legumes during fallow periods. Pressmud is a major by-product when sugar is produced from sugarcane by the sulfitation process. In recent years, several studies have evaluated the relative agronomic and nutrient supplying capabilities of different organic materials (Singh 1984; Meelu and Morris 1987; Nagarajah 1988; Maskina et al. 1988; Yadvinder-Singh et al. 1991; Panda et al. 1995). But the literature on the N and C mineralization of different manures varying widely in N content and C:N ratio and their influence on gaseous N losses from upland and flooded soils is meager.

N can be lost by nitrate leaching to deeper soil layers (Aulakh et al. 2000a) and gaseous emissions of $NH_3$ (Aulakh and Bijay-Singh 1997) and $N_2O$ to the atmosphere (Ottow and Benckiser 1994; Sommer et al. 1998; Fey et al. 1999). In addition to reduced fertilizer use-efficiency, these mechanisms cause environmental pollution. The relative importance of these processes, however, can vary widely, depending on the agricultural system and the environment. For example, losses of N through $NH_3$ volatilization are not favored in porous soils as ammonium N would be transported to lower soil depths along with percolating irrigation water (Aulakh and Bijay-Singh 1997), but leaching of nitrate beyond plant rooting zone could be substantial in rice fields fertilized with inorganic fertilizer N (Aulakh et al. 2000a). On the other hand, use of manures could minimize potential nitrate leaching as they act as slow release fertilizers synchronizing N supply with plant need (Aulakh et al. 2000a). Unfortunately, direct evidence on N losses through denitrification in semiarid subtropical soils is limited. As C substrate availability is one of the key controls over denitrification (Beauchamp et al. 1989; Aulakh et al. 1991a; Dendooven et al. 1996; Qian et al. 1997), the potential for denitrification losses in the field cannot be adequately estimated until C availability from organic manures is well understood. Better understanding of N cycling processes in irrigated semiarid subtropical soils, particularly the microbial transformations of organic amendments to plant-available N and gaseous N forms is needed for most efficient use of soil and organic manure N, for evaluation of agricultural management effects on air quality, for determining the potential of denitrification, and for aiding in the selection of N management practices for sustainable agriculture.

We initiated controlled growth chamber studies to investigate the influence of inorganic fertilizer N and organic manures on mineralization, nitrification, availability of nitrate, organic C supply, and gaseous N losses via denitrification in a semiarid subtropical soil under upland, nearly saturated, and flooded conditions. The results on the influence of inorganic fertilizer N applied through nitrate and ammoniacal sources are reported by Aulakh et al. (2000b) and those of different manures (cattle manure, pressmud, green manure and poultry manure) are presented here.

## Materials and methods

The soil used in this study was a Fatehpur sandy loam (Typic Ustochrepts) collected from the Ap horizon of a field under annual double crop rice-wheat rotation at Punjab Agricultural University Research Farm, Ludhiana, India. The important characteristics of this soil, preparation of repacked soil cores in vials, and procedures for gas sampling and mineral N analysis have been elaborated by Aulakh et al. (2000b).

Treatments consisted of three moisture regimes [60, 90 and 120% water-filled pore space (WFPS), which simulated upland, nearly saturated and flooded soil conditions, respectively] and five N rates (control without N, and 100 mg N $kg^{-1}$ through cattle manure, pressmud, green manure and poultry manure). Cattle and poultry manures were collected in bulk from Punjab Agricultural University Dairy and Poultry Farms, respectively. Pressmud was procured from a sugar mill. Green manure, collected from a 50-day-old crop of *Sesbania aculeata* and whole plant samples of above-ground material were chopped to 4 ± 1 mm size. Manures were oven-dried at 60 °C for 3 days and all, except green manure, were ground to pass through a 2-mm sieve to obtain a uniform material and facilitate incorporation in the soil. Important characteristics of these manures are presented in Table 1.

Seven batches, each of 90 repacked soil cores (three moisture regimes × five N treatments × three replications × two sets), were prepared by placing moist pre-conditioned soil (80 g on oven-dry basis) either pre-mixed with an appropriate amount of manure (Table 1) or without any manure in clear 40-mm-diameter plastic vials. The soil in each vial was then hand-compacted to a bulk density of 1.55 g $cm^{-3}$. Each repacked core had a soil depth of 75 mm, which is considered the optimum depth to simulate field conditions for obtaining reliable and quantitative information regarding N transformations in soils under flooded conditions (Khera et al. 1999). Seven batches were incubated for 0-, 1-, 2-, 4-, 8-, 12- and 16-day periods in a randomized complete block design (RCBD).

Distilled water was added dropwise using a fine jet pipette to obtain 60, 90 and 120% WFPS. Then each vial was covered with a perforated polyethylene sheet to permit gaseous exchange but restrict evaporation of water. Thereafter, the vials were incubated at 35 °C, which is the optimum temperature for microbial activity,

**Table 1** Characteristics of organic manures and amount of manure-C added to soil

| Organic manure | Characteristics of manures | | | Amount of manure added[a] | Amount of C added through manure |
|---|---|---|---|---|---|
| | N content (g $kg^{-1}$) | C content (g $kg^{-1}$) | C:N ratio | (g $kg^{-1}$ soil) | (g $kg^{-1}$ soil) |
| Cattle manure | 6.0 | 210 | 35 | 16.67 | 3.50 |
| Pressmud | 17.4 | 380 | 22 | 5.75 | 2.19 |
| Green manure | 26.8 | 375 | 14 | 3.73 | 1.40 |
| Poultry manure | 19.5 | 234 | 12 | 5.13 | 1.20 |

[a] Added on N-equivalent basis: 100 mg N $kg^{-1}$ soil added through each manure

including nitrification, in semiarid subtropical soils (Bhupinderpal-Singh et al. 1993). Water loss through evaporation, if any, was replaced every 2 days.

Of the two sets of each treatment in each batch, one set was used for measuring denitrification, using the acetylene ($C_2H_2$) inhibition technique (Aulakh et al. 1984). Individual vials were placed, 24 h before the termination of incubation of a batch, in a 0.87-l glass jar and sealed with screw-cap lid in which a serum stopper had been fitted. Then in order to determine the rate of denitrification by inhibiting the reduction of $N_2O$ to $N_2$ with $C_2H_2$, 10% (v/v) of head air of each jar was replaced with $C_2H_2$, and jars were incubated for 24 h at 35 °C. Duplicate 2 $cm^3$ gas samples of the headspace atmosphere of each jar were removed for determination of $N_2O$ and $CO_2$ by gas chromatography (Aulakh et al. 1991b). Data were corrected for the solubility of $N_2O$ and $CO_2$ in the soil water (Moraghan and Buresh 1977). Estimates of cumulative denitrification losses were calculated from averaging $N_2O$-N rates throughout the period by weighing the interval of two measurements (Cai et al. 1997). The same procedure was used for estimating cumulative flux of $CO_2$-C.

As $C_2H_2$ inhibits nitrification (Aulakh et al. 1984), soil cores of the second set of treatments of each batch were used for determining mineralization, nitrification of soil organic N and added manure N. At the termination of incubation of a batch, whole soil from each vial was extracted with 2 M KCl (1-h shaking), filtered, and analyzed for ($NO_3^- + NO_2^-$)-N and $NH_4^+$-N using a micro-Kjeldahl procedure (Mulvaney 1996).

Apparent mineralization of manure-N and C was calculated as follows:

% mineralization of manure-N = 100 $(N_M - N_0)/(N_{APP})$,

where $N_M$ = mineral N ($NH_4^+$-N + $NO_3^-$-N) in soil plus denitrified N in manure-amended soil (mg N $kg^{-1}$ soil), $N_0$ = mineral N plus denitrified N in control soil (mg N $kg^{-1}$ soil), and $N_{APP}$ = rate of applied manure-N (100 mg N $kg^{-1}$ soil).

% mineralization of manure-C = 100 $(C_M - C_0)/(C_{APP})$,

where $C_M$ = cumulative $CO_2$-C emitted from manure-amended soil (mg C $kg^{-1}$ soil), $C_0$ = cumulative $CO_2$-C emitted from control soil (mg C $kg^{-1}$ soil), and $C_{APP}$ = rate of applied manure-C as presented in Table 1 (mg C $kg^{-1}$ soil).

Statistical analysis of experimental data was accomplished by standard Analysis of Variance in RCBD (Cochran and Cox 1950) followed by mean separation within three moisture regimes using the least significant difference (LSD) test for significance at the 0.05 level of probability. Relationships between C:N ratio and N content of manure with net increase in cumulative denitrification losses over 16 days (denitrified N in manure-amended minus control soils) were calculated using best-fit regression equations.

## Results and discussion

### Mineralization of applied manure N

The mineral N ($NH_4^+$-N + $NO_3^-$-N) content increased from 39.8 mg N $kg^{-1}$ at the beginning of incubation to 55.5 mg N $kg^{-1}$ after 16 days in control soil (without fertilizer N application) under upland condition (Table 2). Net accumulation of mineral N (mineral N in manure-amended soil minus mineral N in control soil) in cattle manure, pressmud, poultry manure and green manure treatments after 16 days was 9, 16, 26 and 40 mg N $kg^{-1}$, respectively. Apparent mineralization of cattle manure-, pressmud-, poultry manure- and green manure-N after 16 days was 12, 20, 29 and 44%, respectively. Mineralization of N was quick in all manures, except pressmud. Incorporation of pressmud caused immobilization of soil mineral N during the initial 4 days followed by fast mineralization that eventually exceeded the accumulation of mineral N in cattle manure amended soil at the end of 16 days incubation. The rate of manure-N mi-

**Table 2** Effect of manures on $NH_4^+$-N and $NO_3^-$-N (mg N $kg^{-1}$) in upland, nearly saturated, and flooded soil (incubated without acetylene)

| Organic manure | 0 days | | 2 days | | 4 days | | 8 days | | 12 days | | 16 days | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N | $NO_3^-$-N | $NH_4^+$-N | $NO_3^-$-N |
| Upland (60% WFPS) | | | | | | | | | | | | |
| Control | 1.8 | 38.0 | 1.1 | 42.6 | 1.8 | 44.3 | 1.8 | 47.7 | 1.5 | 49.9 | 1.6 | 53.9 |
| Cattle manure | 4.5 | 39.4 | 4.7 | 45.4 | 4.5 | 46.8 | 4.0 | 49.7 | 4.2 | 52.8 | 4.5 | 59.9 |
| Pressmud | 3.6 | 38.0 | 4.4 | 36.4 | 5.1 | 36.5 | 5.9 | 48.2 | 5.5 | 54.2 | 5.1 | 66.5 |
| Green manure | 2.6 | 41.7 | 4.5 | 45.4 | 4.4 | 54.3 | 5.4 | 65.2 | 5.6 | 76.7 | 5.9 | 90.1 |
| Poultry manure | 13.0 | 43.4 | 8.0 | 45.1 | 6.4 | 50.9 | 6.0 | 68.7 | 6.1 | 64.7 | 6.2 | 75.6 |
| LSD (0.05) | 1.9 | 3.6 | 1.2 | 4.3 | 1.3 | 5.4 | 1.2 | 7.5 | 2.0 | 5.5 | 2.1 | 6.0 |
| Nearly saturated (90% WFPS) | | | | | | | | | | | | |
| Control | 1.8 | 38.0 | 2.8 | 27.2 | 3.7 | 20.5 | 3.7 | 5.7 | 4.1 | 2.4 | 4.7 | 0.4 |
| Cattle manure | 4.5 | 39.4 | 7.8 | 16.8 | 7.9 | 7.3 | 8.3 | 0.0 | 8.5 | 0.0 | 8.5 | 0.0 |
| Pressmud | 3.6 | 38.0 | 7.6 | 9.4 | 7.7 | 4.6 | 8.0 | 0.0 | 8.5 | 0.0 | 8.8 | 0.0 |
| Green manure | 2.6 | 41.7 | 10.0 | 2.5 | 11.1 | 0.0 | 12.2 | 0.0 | 14.9 | 0.0 | 15.7 | 0.0 |
| Poultry manure | 13.0 | 43.4 | 15.4 | 21.0 | 17.8 | 9.6 | 18.8 | 8.2 | 20.1 | 0.0 | 20.5 | 0.0 |
| LSD (0.05) | 1.9 | 3.6 | 2.1 | 2.9 | 2.4 | 2.9 | 3.0 | 1.7 | 2.5 | 0.5 | 3.0 | 0.2 |
| Flooded (120% WFPS) | | | | | | | | | | | | |
| Control | 1.8 | 38.0 | 5.6 | 25.0 | 6.0 | 19.7 | 6.0 | 8.1 | 7.9 | 3.3 | 9.6 | 0.5 |
| Cattle manure | 4.5 | 39.4 | 10.7 | 14.6 | 12.0 | 5.4 | 12.3 | 0.0 | 14.7 | 0.0 | 16.2 | 0.0 |
| Pressmud | 3.6 | 38.0 | 7.9 | 7.3 | 9.3 | 3.2 | 11.0 | 0.0 | 13.4 | 0.0 | 17.5 | 0.0 |
| Green manure | 2.6 | 41.7 | 15.0 | 2.1 | 20.7 | 0.0 | 25.1 | 0.0 | 32.6 | 0.0 | 40.4 | 0.0 |
| Poultry manure | 13.0 | 43.4 | 20.3 | 18.2 | 27.5 | 7.2 | 35.9 | 6.1 | 2.1 | 0.0 | 48.0 | 0.0 |
| LSD (0.05) | 1.9 | 3.6 | 2.8 | 3.0 | 2.5 | 3.0 | 3.0 | 1.1 | 4.0 | 0.8 | 4.2 | 0.3 |

neralization varied widely among different manures and was best described by polynomial regression equation. Apparent mineralization of added manure-N was inversely related to C:N ratio ($R^2=0.703$, $P=0.05$) and directly to N content of manure ($R^2=0.964$, $P=0.01$). The rapid mineralization of green manure-N confirmed the findings of a recent laboratory incubation study of Khera et al. (1999) where 36% of *Sesbania*-N mineralized as soil mineral N within 15 days.

In nearly saturated and flooded soils where aeration was restricted, mineralization was relatively low and nitrification was reduced, resulting in accumulation of $NH_4^+$-N (Table 2); $NO_3^-$ rapidly disappeared due to concurrent denitrification. Apparent mineralization of manure-N in nearly saturated soils ranged from –27% to +7% of the corresponding treatments under flooded conditions.

## Mineralization and recovery of applied manure C

Soil microbial activity (indicated by $CO_2$ production) was very high during the initial 8 days of incubation and $CO_2$-C production rates were highest in upland followed by nearly saturated and flooded soils (data not shown). Apparent mineralization of added C over 16 days ranged from 6% to 8% in cattle manure, 17% to 19% in pressmud, 36% to 48% in green manure and 35% to 50% in poultry manure in soils incubated under different moisture regimes (Table 3). As was observed for mineralization of manure-N in upland condition, mineralization of manure-C under all three water regimes was, in general, inversely related to initial C:N ratio of manure ($R^2=0.690$, $P=0.05$). One exception was, however, noted between green manure (C:N = 14) and poultry manure (C:N = 12) under nearly saturated and flooded conditions, where mineralization of C from poultry manure was lower than green manure. Poultry manure is a plant material that has passed through the digestive tract of a bird. Hence, much of the readily decomposable C could has been utilized by the bird. Reduced mineralization of poultry manure when compared to green manure may thus be due to reduced decomposable C quality in the poultry manure (e.g. recalcitrant C compounds) and its lower N content than of green manure (Table 1). Slowest mineralization of C from cattle manure corroborate with the findings of Sarmah and Bordoloi (1994), which indicated cattle manure could be a good source for building soil organic matter on long-term basis.

## Denitrification

Denitrification losses from manure-amended upland soils were very low with $N_2O$ evolution rates ranging from 0.13 to 1.15 mg N kg$^{-1}$ day$^{-1}$ (Fig. 1) and cumulative N losses of 4.5–8.2 mg N kg$^{-1}$ over a period of 16 days (Table 4). Nevertheless, incorporation of manures enhanced the rate of denitrification by 60–82% in the upland soil. Decomposition of organic materials and mineralization of organic C (Table 3) increased demand for $O_2$ and created partially anaerobic conditions resulting into enhanced rates of denitrification (Aulakh and Rennie 1987; Rice et al. 1988; Qian et al. 1997).

Under nearly saturated and flooded conditions, denitrification rates were several fold greater than under upland conditions (Fig. 1) apparently due to a depletion of $O_2$ that created anaerobic conditions. The increase in the rate of denitrification was almost instant. The $N_2O$-N flux rates in nearly saturated and flooded control soils increased 3- to 12-fold with maximum denitrification rates of 2.1 and 3.2 mg N kg$^{-1}$ day$^{-1}$ after 2 days of incubation, respectively. After 4 days, the rates decreased and remained very low for the remaining period of study. Incorporation of cattle manure, pressmud, poultry and green manure in nearly saturated soils increased the $N_2O$ flux with maximum peaks of 3.3, 5.7, 7.7 and 8.2 mg N kg$^{-1}$ day$^{-1}$ recorded on day 2, respectively. The corresponding values for flooded soil were 4.1, 6.8, 7.4 and 10.0 mg $N_2O$-N kg$^{-1}$ day$^{-1}$ (Fig. 1). Thereafter denitrification activity decreased rapidly. Cumulative denitrification losses from soils incubated without and with manures under nearly saturated and flooded conditions revealed that 34–55% losses occurred during day 1 to day 4, 25–31% from day 5 to day 8, 15–25% from day 9 to day 12 and 9–17% from day 13 to day 16 (Table 4). Manure-amended nearly saturated soils supported 14–35% higher denitrification than in flooded soils.

Denitrification potential and rates in soils are controlled by the amount of $NO_3^-$ and C susceptible to mi-

**Table 3** Apparent mineralization of manure-C as $CO_2$-C in upland, nearly saturated and flooded soil incubated over 16 days

| Organic Manure | % mineralization of manure-C[a] | | | |
|---|---|---|---|---|
| | Upland | Nearly saturated | Flooded | Mean |
| Cattle manure | 7.7 | 6.4 | 6.3 | 6.5 |
| Pressmud | 18.7 | 17.4 | 17.3 | 17.8 |
| Green manure | 47.6 | 40.9 | 36.0 | 41.5 |
| Poultry manure | 50.4 | 38.9 | 34.8 | 41.4 |
| LSD (0.05) | 2.2 | 2.0 | 2.6 | 1.6 |

[a] % mineralization of manure-C = 100 [$CO_2$-C in manure treatment (mg C kg$^{-1}$ soil) – $CO_2$-C in control (mg C kg$^{-1}$ soil)]/added manure-C (mg C kg$^{-1}$ soil)

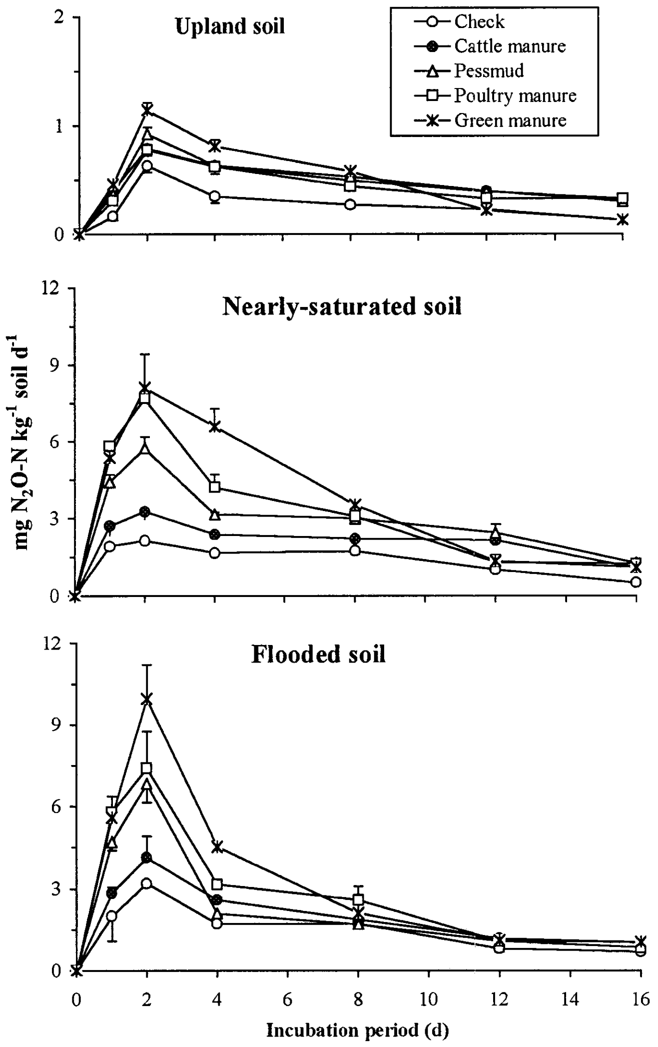

**Fig. 1** Rate of denitrification (as $N_2O$-N using acetylene inhibition technique) in upland, nearly saturated and flooded soil incubated without any manure or with organic manures. (Note differences in the scale on *Y*-axis). *Bars* represent SD, shown in only one direction for clarity

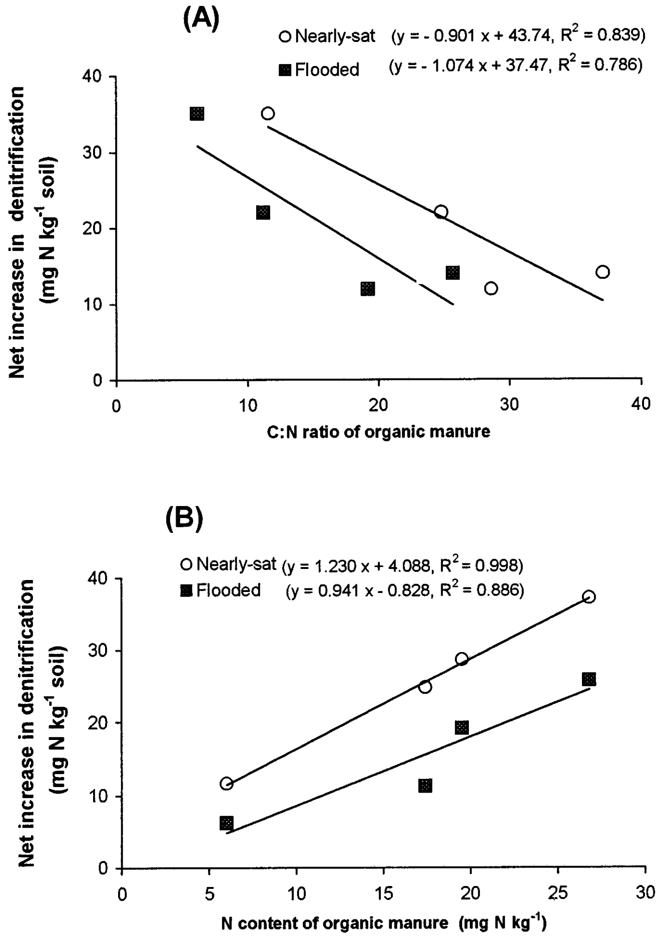

**Fig. 2** Relationship of net increase in cumulative denitrification losses over 16 days in response to applied manures (denitrified N in manure-amended minus control soils) in nearly saturated and flooded soil with (A) C:N ratio of manure and (B) N content of manure

neralization (Bijay-Singh et al. 1988; Rice et al. 1988). In the present study, the amount of $NO_3^-$-N at the beginning of the incubation ranged from 38.0 to 43.4 mg N kg$^{-1}$ in different treatments (Table 2). Soil $NO_3^-$ remained available in soils incubated without manure due to relatively lower denitrification. $CO_2$-C emissions from manure-amended soils were relatively high during the initial period of incubation, which coincided with patterns for denitrification (data not shown). Evolution of $CO_2$-C in nearly saturated and flooded soils peaked after 2 days in control (11.8 and 7.4 mg C kg$^{-1}$ day$^{-1}$), cattle manure (60.2 and 40.7 mg C kg$^{-1}$ day$^{-1}$), pressmud (93.1 and 49.6 mg C kg$^{-1}$ day$^{-1}$), poultry manure (96.4 and 64.6 mg C kg$^{-1}$ day$^{-1}$) and green manure (98.3 and 59.5 mg C kg$^{-1}$ day$^{-1}$). After 8 days, the $CO_2$-C emissions from manure-amended soils ranged from 10.5 to 43.7 mg C kg$^{-1}$ day$^{-1}$, indicating that C supply probably did not limit denitrification throughout the incubation period. Hence, the rapid decreases in denitrification rates (Fig. 1) were the result of limited $NO_3^-$ substrate during this time period (Table 2). Conversely, low rates of denitrification observed in control soils, where $NO_3^-$ remained present during the later period (8–16 days), were due to the limited C availability to denitrifying organisms. The enhanced denitrification losses with manures when compared to control were, in general, inversely related to initial C:N ratio of manure (Fig. 2a) and directly to N content of manure in nearly saturated and flooded soils (Fig. 2b). Thus the N loss was maximal with green manure (C:N = 14) and lowest with cattle manure (C:N = 35). It is, however, interesting to note one exception that green manure resulted in significantly higher cumulative losses than poultry manure (C:N = 12). This could be due to lower availability of organic C through poultry manure due to its reduced C mineralization (Table 3). It has previously been documented that C:N ratio of crop residues correlates well with N mineralization (Ford et al. 1989) and denitrifica-

**Table 4** Effect of manures on cumulativedenitrification losses (mg N kg$^{-1}$) in upland, nearly saturated and flooded soil

| Organic manure | Incubation period | | | | |
|---|---|---|---|---|---|
| | 0–4 days | 5–8 days | 9–12 days | 13–16 days | Total 0–16 days |
| | | | Upland (60% WFPS) | | |
| Control | 1.6 | 1.2 | 1.0 | 0.7 | 4.5 |
| Cattle manure | 2.6 | 1.8 | 1.7 | 1.4 | 7.5 |
| Pressmud | 2.7 | 2.3 | 1.6 | 1.3 | 7.9 |
| Green manure | 3.4 | 2.7 | 1.4 | 0.7 | 8.2 |
| Poultry manure | 2.4 | 2.0 | 1.5 | 1.3 | 7.2 |
| LSD (0.05) | 0.3 | 0.5 | 0.2 | 0.2 | 0.5 |
| | | | Nearly saturated (90% WFPS) | | |
| Control | 7.7 | 6.9 | 5.2 | 2.9 | 22.7 |
| Cattle manure | 11.2 | 8.7 | 8.5 | 6.0 | 34.4 |
| Pressmud | 17.8 | 12.3 | 10.6 | 6.9 | 47.6 |
| Green manure | 27.4 | 18.8 | 8.7 | 4.9 | 59.8 |
| Poultry manure | 23.7 | 14.0 | 8.0 | 5.6 | 51.3 |
| LSD (0.05) | 1.7 | 0.8 | 1.0 | 1.1 | 2.9 |
| | | | Flooded (120% WFPS) | | |
| Control | 9.4 | 6.9 | 4.6 | 3.1 | 24.0 |
| Cattle manure | 13.0 | 7.7 | 5.2 | 4.3 | 30.2 |
| Pressmud | 18.1 | 7.5 | 5.3 | 4.3 | 35.2 |
| Green manure | 27.3 | 12.1 | 6.0 | 4.3 | 49.7 |
| Poultry manure | 21.6 | 11.2 | 6.6 | 3.8 | 43.2 |
| LSD (0.05) | 0.8 | 1.1 | 0.9 | 0.5 | 2.9 |

tion (Aulakh et al. 1991a). Our results further demonstrate that in case of organic manures varying in N content and C:N ratio, both C:N ratio and N content should be considered to predict denitrifying activity in manure-amended soils. Substantially greater denitrification in manure-amended nearly saturated soils than flooded soils (Table 4) was presumably due to the enhanced supply of organic C, as was evident from relatively higher $CO_2$-C peaks and cumulative mineralized C, especially in green manure and poultry manure treatments (Table 3).

## Conclusions

Mineralization of cattle manure-, pressmud-, poultry manure- and green manure-N in upland soil over 16 days resulted in the net accumulation of 9, 16, 26 and 40 mg mineral N kg$^{-1}$, respectively. Considering 7.5 cm soil depth and bulk density of 1.55 g cm$^{-3}$, these values correspond to about 11, 19, 30 and 47 kg N ha$^{-1}$, respectively. These results suggest that incorporation of narrow C:N ratio poultry and green manures at seeding may release sufficient mineral N to synchronize N supply with crop needs during early growth period. However, starter N may be required where wide C:N ratio cattle manure and pressmud are used. The lowest recoveries of C from cattle manure indicate that long-term use of cattle manure could help build up of soil organic matter. Under anaerobic soil conditions, mineralized N accumulated mainly as $NH_4^+$-N suggesting that denitrification losses would be relatively reduced due to non-availability of $NO_3^-$. Since rice plants prefer $NH_4^+$ to $NO_3^-$ this may represent a more efficient system for meeting the N needs of rice crop. These findings should form the basis for future field investigations for formulating the integrated management of manures with inorganic fertilizers for developing efficient management practices for sustainable agriculture.

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