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Denitrification losses from an irrigated sandy-clay loam under a wheat-maize cropping system receiving different fertilizer treatments

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Abstract Studies were conducted on denitrification in the plough layer of an irrigated sandy-clay loam under a wheat-maize cropping system receiving different fertilizer treatments. The treatments were: N-100 (urea-N at 100 kg ha^{-1} year^{-1}), N-200 (urea-N at 200 kg ha^{-1} year^{-1}), FYM-16 (farmyard manure at 16 tonnes ha^{-1} year^{-1}), FYM-32 (farmyard manure at 32 tonnes ha^{-1} year^{-1}) and the control (unfertilized). Averaged across sampling dates during the wheat season, the denitrification rate as measured by the C_2H_2-inhibition/soil-core incubation method was highest in N-200 (83 g N ha^{-1} day^{-1}), followed by FYM-32 (60 g N ha^{-1} day^{-1}, N-100 (51 g N ha^{-1} day^{-1}), FYM-16 (47 g N ha^{-1} day^{-1}) and the control (33 g N ha^{-1} day^{-1}). During the maize growing season, average denitrification rate was highest in FYM-32 (525 g N ha^{-1} day^{-1}), followed by FYM-16 (408 g N ha^{-1} day^{-1}), N-200 (372 g N ha^{-1} day^{-1}, N-100 (262 g N ha^{-1} day^{-1}) and the control (203 g N ha^{-1} day^{-1}). Denitrification loss integrated over the whole vegetation period was at a maximum under FYM-32 (13.9 kg N ha^{-1}), followed by N-200 (11.8 kg N ha^{-1}), FYM-16 (10.6 kg N ha^{-1}) and N-100 (8.0 kg N ha^{-1}), whereas the minimum was observed for the control (5.8 kg N ha^{-1}). Under both crops, denitrification was significantly correlated with water-filled pore space and soil NO_3^--N. The best multiple regression models accounted for 52% and 70% of the variability in denitrification under wheat and maize, respectively. Results indicated that denitrification is not an important N loss mechanism in this well-drained, irrigated sandy-clay loam under a wheat-maize cropping system receiving fertilizer inputs in the range of 100–200 kg N ha^{-1} year^{-1}.

Key words Acetylene inhibition · Denitrification · Farmyard manure · Irrigated wheat-maize · Urea

Introduction

Denitrification can be an important cause of low nitrogen use efficiency as well as a major source of atmospheric nitrous oxide, which besides acting as a greenhouse gas (Watson et al. 1990) is implicated in the destruction of the stratospheric ozone (Crutzen 1981). Although extensive studies have been conduced since the development of methods for direct measurement of denitrification (Ryden et al. 1979; Mulvaney and Kurtz 1982; Siegel et al. 1982), the process still remains one of the least well-quantified sectors of the terrestrial nitrogen cycle. Quantitative estimates of denitrification vary tremendously. From heavily fertilized irrigated vegetable fields, denitrification loss as high as 200 kg N ha^{-1} year^{-1} has been reported (Ryden and Lund 1980). On the other hand, figures reported by other authors were quite low and ranged between 1.7 to 10 kg N ha^{-1} during the vegetation period (Benckiser et al. 1986, 1987; Mosier et al. 1986; Myrold 1988, Goulding et al. 1993).

In Pakistan, crop husbandry largely depends on irrigation and many other inputs including fertilizer N, annual consumption of which stands at 1.64 million tonnes on 21.93 million ha of the cultivated land (Anonymous 1994). The recovery of the applied fertilizer N is seldom more than 60% under upland conditions in Pakistan (Ahmed 1985). Some laboratory studies conducted on the soils of the Faisalabad region showed that of the total N applied, up to 30% is lost due to NH_3-volatilization (Hamid and Ahmad 1987). However, knowledge about denitrification losses under field conditions in Pakistan is absolutely lacking. Studies were therefore conducted to quantify denitrification losses from some soil-plant systems under irrigated field conditions. This paper reports denitrification losses from the plough layer of an irrigated sandy-clay loam under a wheat-maize cropping system receiving different fertilizers treatments.

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Table 1 Details of fertilizer treatments and some physicochemical properties of the 0–15 cm soil depth

Treatment	Wheat	Maize	TOC (%)	Total N (%)	WHC (%)	pH[a]	Bulk density (g cm^{-3})	Pore space (%)
N[b]-100	50 kg N ha^{-1}	50 kg N ha^{-1}	1.14	0.07	37	7.3	1.44	46.9
N-200	100 kg N ha^{-1}	100 kg N ha^{-1}	1.05	0.09	36	7.3	1.42	47.4
FYM[c]-16	16 tonnes ha^{-1}	None	1.17	0.08	36	7.4	1.42	47.5
FYM-32	32 tonnes ha^{-1}	None	1.18	0.09	37	7.4	1.41	47.6
Control	None	None	0.78	0.07	35	7.4	1.52	43.8

[a] Saturation paste

[b] Urea-N. To each crop, the stated dose of urea-N was applied in two equal parts, one at sowing and the other with the second (in the case of wheat) or the third (in the case of maize) irrigation

[c] Farmyard manure. Stabilized for about 6 months in a pit, all applied in November during land preparation for wheat. The total N applied as FYM-16 and FYM-32 treatments was equivalent to 96 and 192 kg ha^{-1}, respectively; the amount of P_2O_5 applied as FYM-16 and FYM-32 treatments was equivalent to 96 and 192 kg ha^{-1}, respectively, which was balanced in N-100 and N-200 treatments by the application of single superphosphate

Materials and methods

The study site at the Nuclear Institute for Agriculture and Biology, Faisalabad, is located at 73.2° longitude, 31.4° latitude and 183 m above sea level. The area has a semiarid subtropical climate with a mean annual rainfall of 340 mm, most of which occurs in the months of July and August. The hottest months are May and June, with mean maximum temperatures of 39.4 and 41.1 °C, respectively, whereas January is the coldest month with a mean minimum temperature of 5 °C. The soil, which belongs to Hafizabad series, is a deep, well-drained sandy-clay loam and was developed in mixed calcareous medium-textured alluvium derived from the Himalayas in, probably, the late Pleistocene (Anonymous 1967). The site has been under a wheat-maize cropping system receiving different fertilizer treatments since 1980. Twenty experimental plots (7.5×8.5 m) were established for five fertilizer treatments in a randomized complete block design, each with four replicates. The treatments were: N-100 (urea-N at 100 kg ha^{-1} $year^{-1}$), N-200 (urea-N at 200 kg ha^{-1} $year^{-1}$), FYM-16 (farmyard manure at 16 tonnes ha^{-1} $year^{-1}$), FYM-32 (farmyard manure at 32 tonnes ha^{-1} $year^{-1}$) and the control (unfertilized). Details of the fertilizer treatments and some physicochemical characteristics of the plough layer are given in Table 1.

Wheat (*Triticum aestivum* L. cv. Pak-81) was sown on 6 December 1990 and harvested on 5 May 1991, whereas maize (*Zea mays* L. cv. Akbar) was seeded on 29 August 1991 and the fodder harvested on 30 October 1991. Wheat received six irrigations: all were 7.5 cm except the first (pre-planting) and the fourth, which were 10 and 5 cm, respectively. During the maize-season, five irrigations were applied: all were 7.5 cm except the first (pre-planting) and the last, which were 10 and 5 cm, respectively.

For denitrification rate measurements, sampling started about 12 h after irrigation when the field was accessible, and continued until the soil dried to field capacity (5–15 days under wheat and 5–7 days under maize). Denitrification and soil respiration rates under field conditions were measured using the soil-core incubation method (Ryden et al. 1987). Briefly, from each replicate plot four intact soil cores (3×15 cm, diameter×depth) were randomly extracted in PVC sleeves with a sampling device similar to that of Rice and Smith (1982) and placed together in the field incubation jar. The jars (nominal volume, 800 ml) were sealed with a silicone rubber stopper that was provided with a septum port. After replacing the headspace with acid-washed C_2H_2 (0.1 atm) the jars were incubated in holes made within the experimental field. After 4 and 12 h of incubation, the atmosphere in the jars was repeatedly mixed with a 50-ml syringe and a gas sample removed for analyses of N_2O and CO_2. Nitrous oxide was analysed on a Hitachi 263-30 gas chromatograph equipped with a ^{63}Ni-electron capture detector. Analysis of CO_2 was carried out on a Gasukuro Kogyo 370 gas chromatograph equipped with a thermal conductivity detector. After gas sampling the soil from each replicate plot (four cores) was pooled, mixed and sampled for analyses of NO_3^--N and gravimetric moisture content. For determination of the soil NO_3^--N, 20 g of field-moist soil was extracted with 100 ml 2 *N* KCl and the extract analysed for NO_3^--N by micro-Kjeldahl method (Keeney and Nelson 1982). Average soil temperature during incubation was calculated form the maximum and minimum temperatures recorded by glass thermometers inserted at 5 cm depth. Water-filled pore space (WFPS) was calculated as: WFPS = (gravimetric moisture content × soil bulk density)/total soil porosity.

The data were subjected to analysis of variance followed by Duncan's multiple range test and linear regression analysis (Gomez and Gomez 1984). To satisfy the assumption of variance homogeneity, data for denitrification, soil respiration and NO_3^--N were log-transformed before statistical analyses.

Results

Spatial variability

Spatial variability was highest for denitrification rate (average CV = 60%, range = 4–160%) followed by soil NO_3^--N content (average CV = 43%, range = 2–163%) and soil respiration rate (average CV = 25%, range = 3–70%) and was often as large as among sampling dates. However, differences between treatments were significant at the 0.05 level. Water-filled pore space was spatially uniform (average CV = 6%, range = 1–14%).

Treatment effects under wheat

Trends revealed higher denitrification rates in fertilized than unfertilized wheat field at least during the first two irrigation cycles (15 November – 31 December), the period when most of the denitrification occurred under wheat (Fig. 1). During the first irrigation cycle, the denitrification rates in N-100 and FYM-16 were almost similar to the control, whereas FYM-32 and N-200 showed 130% and 159% higher denitrification, respectively ($P<0.05$). Highest denitrification rates under wheat were recorded during the second irrigation cycle, when 49–98% and 34–56% higher rates were observed due to urea and FYM treatments, respectively ($P<0.05$). Although the last four irrigations and two rainfalls near the crop maturity caused very low deni-

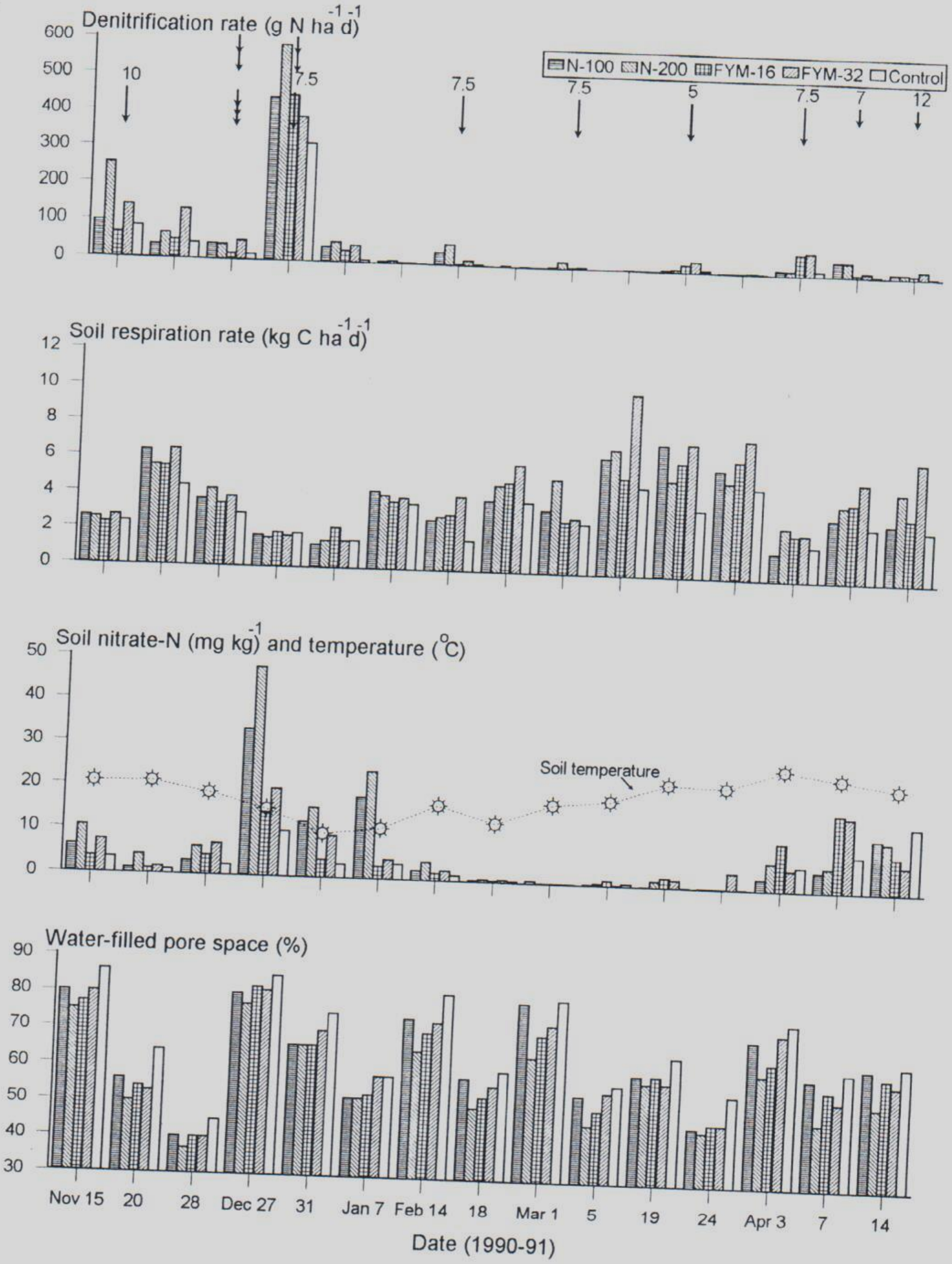


Fig. 1 Denitrification, soil respiration and environmental conditions in the wheat field receiving different fertilizer treatments. *Long arrows* indicate depth (cm) of irrigation; *small arrows*, rainfall (mm); *double-headed arrows*, application of urea to N-100 (25 kg N ha^{-1}) and N-200 (50 kg N ha^{-1}) treatments; *triple-headed arrows*, application of farmyard manure to FYM-16 (16 tonnes ha^{-1}) and FYM-32 (32 tonnes ha^{-1}) treatments

trification, the rates were higher in fertilized plots relative to the control (P<0.05). Average denitrification rates during wheat season were 51, 83, 47, 60 and 33 g N ha^{-1} day^{-1} in N-100, N-200, FYM-16, FYM-32 and the control, respectively. The average rate in N-200 and FYM-32 treatments was not different but was significantly higher than N-100, FYM-16 and the control (P<0.05). The average denitrification rate was comparable for N-100 and FYM-16 treatments but significantly higher than the control (P<0.05). During the wheat season, 84–94% of the total denitrification loss in all treatments, except N-200, occurred in a relatively short spell (26 days) following the first two irrigations (Table 2). For the N-200 treatment, the last irrigation also produced 16% of the total denitrification in addition to the 79% contribution of the first two irrigation cycles.

Fertilizer treatments also influenced the moisture status of the soil. Averaged across sampling dates, WFPS was highest (67%) in the control and lowest (56%) in the N-200 treatment (P<0.05). Increasing the urea application rate from 100 to 200 kg N ha^{-1} caused a 10% reduction while doubling the FYM caused a slight (3%) increase in the average WFPS during the wheat season (P<0.05). The effect of fertilizer treatments at different sampling dates followed almost the same trend as observed for the WFPS averaged across dates. Data on soil NO_3^--N during the

Table 2 Denitrification loss (kg N ha^{-1}) from wheat and maize fields integrated over each irrigation cycle and for the whole crop periods. Values within rows followed by the same *letter* are not significantly different at $P<0.05$ (Duncan's multiple range test). See text for explanation of treatments

Crop	Irrigation applied (cm)	Measurement period	Treatment				
			N-100	N-200	FYM-16	FYM-32	Control
Wheat	10.0	15 Nov–28 Nov	0.72 b	1.36 a	0.60 b	1.49 a	0.59 b
	7.5	27 Dec– 7 Jan	1.33 a	1.76 a	1.28 a	1.22 a	0.83 b
	7.5	14 Feb–18 Feb	0.08 ab	0.15 a	0.01 c	0.04 bc	0.01 c
	7.5	1 Mar– 5 Mar	0.01 bc	0.04 a	0.01 b	0.01 b	0.00 c
	5.0	19 Mar–24 Mar	0.02 a	0.02 a	0.06 a	0.09 a	0.02 a
	7.5	3 Apr–14 Apr	0.29 ab	0.61 a	0.20 ab	0.31 a	0.06 b
		Wheat crop total	2.44 b	3.94 a	2.15 bc	3.15 ab	1.51 c
Maize	10.0	22 Aug– 6 Sep	2.10 bc	2.83 b	4.50 a	4.64 a	1.90 c
	7.5	13 Sep–17 Sep	0.42 c	0.91 bc	1.89 ab	3.47 a	1.03 bc
	7.5	27 Sep– 9 Oct	2.47 a	2.81 a	1.84 a	2.23 a	1.13 b
	7.5	10 Oct–15 Oct	0.53 b	1.29 a	0.23 bc	0.37 b	0.17 c
	5.0	21 Oct–31 Oct	0.04 a	0.04 a	0.03 a	0.05 a	0.02 a
		Maize crop total	5.54 bc	7.87 ab	8.49 a	10.76 a	4.25 c
		Both crops total	7.98 bc	11.81 a	10.64 ab	13.91 a	5.76 c

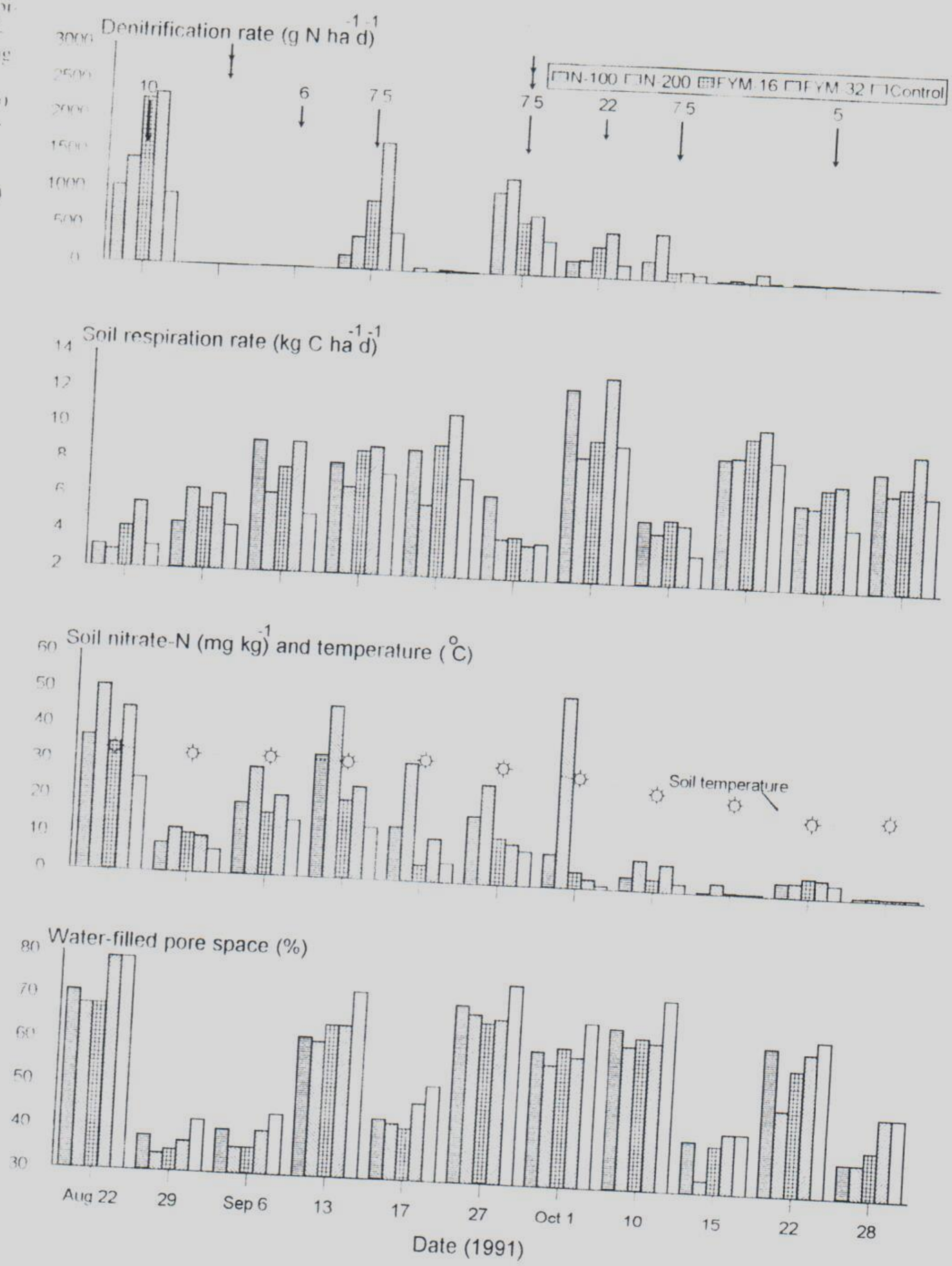
wheat season could be grouped into three distinct phases. The first phase, which was characterized by NO_3-N>2 mg kg^{-1}, occurred from mid-November to mid-February with highest values during December. During this period, the increase due to fertilizer application ranged between 211–360% for urea and 29–111% for FYM treatments ($P<0.05$); the increase was related to the fertilizer application rate. During the second phase (mid-February to March) negligible quantities of NO_3-N were determined in almost all treatments. During the third phase a build-up in NO_3^--N occurred that reached a maximum (10 mg kg^{-1}) during the 2nd week of April but the effect of fertilizer treatments was not consistent. Averaged across sampling dates, the soil NO_3^--N in N-200 was highest (9.2 mg kg^{-1}) whereas the lowest value (3.6 mg kg^{-1}) was recorded for the control ($P<0.05$). In N-100, FYM-16 and FYM-32 treatments, average soil NO_3^--N was comparable and ranged between 4.7 and 6.4 mg kg^{-1}. The effect of fertilizer treatments on soil respiration rate was related to the application rate, producing an average increase of 25–34% and 26–58% due to urea and FYM treatments, respectively. Averaged across sampling dates, soil respiration rate was higher in the fertilized (3.87–4.89 kg C ha^{-1} day^{-1}) than the unfertilized (3.10 kg C ha^{-1} day^{-1}) wheat field. The rates in N-200 (4.15 kg C ha^{-1} day^{-1}) and FYM-32 (4.89 kg C ha^{-1} day^{-1}) were comparable and the same was observed for N-100 (3.87 kg C ha^{-1} day^{-1}) and FYM-16 (3.91 kg C ha^{-1} day^{-1}). However, N-200 and FYM-32 showed significantly higher rates than N-100 and FYM-16 treatments ($P<0.05$).

Treatment effects under maize

Fertilizer treatments had pronounced effects on the rate and magnitude of denitrification (Fig. 2). Except for the second irrigation when N-100 treated plots denitrified at rates lower than the control ($P<0.05$), on other occasions (WFPS>60%) the rate was 8–216% and 27–670% higher in N-100 and N-200 treatments, respectively ($P<0.05$). On irrigation and rainfall events (WFPS>60%), FYM-treated plots denitrified at higher rates than the control ($P<0.05$). At different irrigation and rainfall events, the increase due to FYM application was 35–136% for FYM-16 and 53–236% for the FYM-32 treatment. Averaged across sampling dates during the maize season, denitrification rates in N-100 (262 g N ha^{-1} day^{-1}), N-200 (372 g N ha^{-1} day^{-1}), FYM-16 (408 g N ha^{-1} day^{-1}) and FYM-32 (525 g N ha^{-1} day^{-1}) were significantly higher than the control (203 g N ha^{-1} day^{-1}; $P<0.05$). The difference between N-100 and N-200, or between FYM-16 and FYM-32, was not significant, though FYM-32 has a significantly higher average rate than N-100 ($P<0.05$). Except for N-200, a greater proportion of denitrification loss in different treatments (90–97% of the total) occurred during the first three irrigation cycles (Table 2). While this proportion was slightly lower (83%) for the N-200 treatment, the fourth irrigation cycle also contributed appreciably (16%) to the total denitrification loss.

As observed with wheat, the average WFPS during the maize season was highest (61%) in the control and lowest (50%) in the N-200 treatment ($P<0.05$). In other treatments, the average WFPS was comparable and ranged between 53% and 55%. Virtually similar trends were observed at different sampling dates. During the 4 months fallow between the wheat harvest and the planting of maize, a considerable NO_3-N had accumulated in all treatments. On the occasion of pre-planting irrigation to maize (22 August), the soil NO_3^--N content was comparable in the N-200 (51 mg kg^{-1}) and FYM-32 (45 mg kg^{-1}) treatments but higher than the N-100 (37 mg kg^{-1}), FYM-16 (35 mg kg^{-1}) and control treatments (25 mg kg^{-1}; $P<0.05$). Following a decrease at land preparation, NO_3^--N again increased due to urea application in the N-100 and N-200 treatments. Due to mineralization/nitrification, a build-up in soil NO_3-N was also observed in FYM treatments and the control, but the contents remained lower than those under urea treatments. During mid-October when the soil was almost depleted in NO_3-N, N-200 still showed 3 mg kg^{-1} of NO_3-N. Secondary peaks in soil NO_3^--N were recorded on 22 October and ranged between 3.7–5.3 mg kg^{-1}, the higher values being for FYM treatments.

Fig. 2 Denitrification, soil respiration and environmental conditions in the maize field receiving different fertilizer treatments. *Long arrows* indicate depth (cm) of irrigation; *small arrows*, rainfall (mm); *double-headed arrows*, application of urea to N-100 (25 kg N ha^{-1}) and N-200 (50 kg N ha^{-1}) treatments



By the end of October, when the fodder was harvested, soil NO_3^--N in all treatments fell to <1 mg kg^{-1}. Averaged across sampling dates during the maize season, the soil NO_3^--N was higher in the fertilizer treatments (10.4–24.1 mg kg^{-1}) than the control (7.6 mg kg^{-1}) with the maximum recorded in the N-200 treatment ($P<0.05$). The two FYM treatments did not differ but increasing the urea application rate from 100 to 200 kg N ha^{-1} $year^{-1}$ produced an 80% increase in the average NO_3^--N ($P<0.05$). Average soil respiration rate during the maize growing season was 7.57, 6.32, 7.35, 8.36 and 6.08 kg C ha^{-1} day^{-1} under the N-100, N-200, FYM-16, FYM-32 and control treatments, respectively. The rate was significantly higher in the fertilizer treatments than the control ($P<0.05$) except the N-200 treatment, in which the rate was similar to that of the control. However, the two application rates of urea or FYM did not significantly differ with respect to the average soil respiration rate.

Factors controlling denitrification

Simple linear regression analyses were performed to assess the influence of individual factors on denitrification rate (Table 3). Combining the data for both crops ($n=130$) revealed a highly significant correlation of denitrification

Table 3 Factors explaining the variation in denitrification rate in wheat and maize fields

Crop	Factor	r[a]	Additive R^2[b]
Wheat	Water-filled pore space	0.370***	0.14
	Log NO_3-N	0.675***	0.51
	Log respiration rate	0.481***	0.51
	Soil temperature	0.101	0.54
Maize	Water-filled pore space	0.799**	0.64
	Log NO_3-N	0.290*	0.64
	Log respiration rate	0.111	0.71
	Soil temperature	0.167	0.72
Both crops	Water-filled pore space	0.495***	0.25
	Log NO_3-N	0.519***	0.45
	Log respiration rate	0.099	0.54
	Soil temperature	0.261***	0.54

* $P<0.05$; ** $P<0.01$; ***$P<0.001$

[a] Simple correlation coefficients

[b] Proportion of the variation explained by the combination of the factor plus all preceding factors: all multiple correlation coefficients are significant at the $P<0.01$ level

rate with soil NO_3-N, WFPS and temperature. Under wheat ($n=75$), soil NO_3^--N was still the most important factor governing denitrification, followed by WFPS, whereas under maize ($n=55$), WFPS was the most important factor followed by NO_3-N. Under wheat denitrification was negatively correlated with soil respiration, whereas under maize the relationship was non-significant. The combined effect of different edaphic factors on denitrification was evaluated by multiple linear regression analyses (Table 3). The best multiple regression models obtained by the test of significance technique were:

1. For both crops ($n=130$: $R^2=0.539$: $P<0.01$. Regression equation: $\log D=0.056\ (W) + 0.786\ (\log N) + 1.818\ (\log R) - 3.719$
2. For wheat ($n=75$): $R^2=0.516$: $P<0.01$. Regression equation: $\log D=0.019\ (W) + 0.812\ (\log N) - 0.433$
3. For maize ($n=55$): $R^2=0.698$: $P<0.01$. Regression equation: $\log D=0.089\ (W) + 1.191\ (\log R) - 5.118$

where D=denitrification rate (g N ha^{-1} day^{-1}); W=soil WFPS (%); N=soil NO_3-N content (mg kg^{-1}) and R=soil respiration rate (kg C ha^{-1} day^{-1}).

Discussion

The pattern of spatial variability in denitrification, soil respiration, soil NO_3^--N and WFPS is consistent with some earlier reports (Ryden and Dawson 1982; Myrold 1988; Groffman and Tiedje 1989; Goulding et al. 1993; Estavillo et al. 1994). There was an inverse relationship between denitrification rate and %CV ($P<0.05$), which agrees with the results of Terry et al. (1986) who found lowest CVs during the period of peak denitrification. The higher WFPS in the control than the fertilizer-treated plots may be attributed to poor plant growth extracting less water. However, denitrification rates were generelly lower in the control plots due to substrate limitations. An increase in the rate and magnitude of denitrification due to application of mineral fertilizers has been reported from agricultural (Mosier et al. 1986; Bronson et al. 1992) and grassland soils (Ryden 1983; Estavillo et al. 1994). As found in the present study and in earlier reports (Ryden 1983; Corre et al. 1990), the extent of denitrification loss is also influenced by the rate of N application. Like mineral fertilizers, organic amendments such as animal slurries and green manures are also known to increase denitrification (Kapp et al. 1990; Estavillo et al. 1994). An increase in denitrification loss with increasing N application rate in cow slurry has also been reported (Estavillo et al. 1994). The higher denitrification from the urea- than the FYM-treated wheat field may be attributed to the higher soil NO_3-N in urea treatments. Using equivalent amounts of applied N, Kapp et al. (1990) also found higher soil NO_3-N and denitrification loss from mineral- than slurry-treated ryegrass fields. However, despite the higher soil NO_3-N in urea than FYM treatments, the latter denitrified at higher rates during the maize season. It appears that the effect of carbon contained in FYM was masked during the wheat season due to the higher carbon availability under this crop. When carbon availability became lower during the maize season, the effect of FYM-carbon in enhancing denitrification became apparent. This is supported by the higher carbon availabilty in soil under wheat than under maize (Mahmood et al. 1997). It also seems that the effect of FYM-carbon was an indirect one i.e. by promoting anoxic microsites rather than directly acting as energy source for denitrifiers. Since the denitrification potential of the soil (data not presented) was always several times higher than the actual denitrification rate, the latter was not limited by the supply of available carbon.

Denitrification rates >100 g N ha^{-1} day^{-1} were recorded with NO_3-N contents of >1 mg kg^{-1}, which agrees with the results of Estavillo et al. (1994) but is half the value of NO_3-N reported by Jordan (1989). Similarly, the lower limit for soil NO_3^--N content (2.5 mg kg^{-1}) observed for denitrification rates >200 g N ha^{-1} day^{-1} is also comparable to that reported by Estavillo et al. (1994) but almost half the level reported by Ryden (1983). During the present study, however, the lower limit of WFPS (60%) required to support a denitrification rate of >100–200 g N ha^{-1} day^{-1} is much less than the values (70–74%) reported in other field studies (Jordan 1989; Estavillo et al. 1994). Since the minimum soil temperature to support denitrification rates of >100–200 g N ha^{-1} day^{-1} in the present study (15 °C) is higher than the values reported by these authors (4–5.8 °C), the higher denitrification rates were maintained even at a lower WFPS. The minimum soil water content for denitrification to occur is known to decrease with increasing soil temperature (Bijay-Singh et al. 1989).

As found in the present study, pulses of denitrification after irrigation or rainfall and their strong correlation with soil moisture are well documented (Ryden and Lund 1980; Mosier et al. 1986; Bronson et al. 1992). The negative

Table 4 Influence of soil NO_3^--N concentration on denitrification rate during the maize season

Sampling date	Soil NO_3^--N (mg kg^{-1})	Denitrification rate (g N ha^{-1} day^{-1})	WFPS (%)	Soil respiration rate (kg C ha^{-1} day^{-1})	Soil temperature (°C)
1 Oct	1.0	184	68	9.6	29.8
10 Oct	3.7	256	67	5.5	26.3
27 Sep	10.9	807	68	3.9	31.8
13 Sep	24.9	1726	65	9.1	31.8
22 Aug	34.7	2253	68	4.2	33.5

correlation between denitrification and soil respiration could be due to the negative effect of WFPS on soil respiration observed both under wheat ($r=-0.676$; $P<0.001$) and maize ($r=-0.413$; $P<0.01$). The significant relationship between denitrification and soil NO_3^--N recorded in the present study confirms that under field conditions the process may be limited by NO_3^--N (Benckiser et al. 1987; Bronson et al. 1992; Estavillo et al. 1994). Although in some field studies denitrificaion is reported to be dependent on NO_3^--N below 5–10 mg kg^{-1} (Ryden 1983; Estavillo et al. 1994), the reported K_m values for soil denitrification vary between 0.7 (Yoshinari et al. 1977) and 48 mg N kg^{-1} (Kohl et al. 1976). In the present study, the denitrification rate increased linearly ($r=0.975$; $P<0.001$) up to soil NO_3^--N concentrations as high as 34.7 mg kg^{-1} (Table 4), which is much higher than the values reported in other field studies (Ryden 1983; Estavillo et al. 1994). This discrepancy may be due to the differences in carbon availability, since the NO_3^--N concentration above which denitrification is directly influenced is known to increase with the quantity of available carbon (Kohl et al. 1976; Thompson 1989). Multiple regression analyses also revealed soil NO_3^--N and WFPS as the principal determinants of denitrification under wheat and maize, respectively. Inclusion of WFPS and soil respiration improved the predictability of the multiple regression models for wheat and maize, respectively. In some forest soils, Vermes and Myrold (1992) also found different combinations of factors governing denitrification during different seasons. The amount of variation explained by multiple regression models in the present study (52–70%) compares reasonably with other field studies in which 25–70% of variability in denitrification was explained by different combinations of edaphic factors (Benckiser et al. 1987; Myrold 1988; Vermes and Myrold 1992; Estavillo et al. 1994).

Total denitrification loss during the vegetation period in terms of the applied fertilizer N was low and ranged between 2–3% and 4–5% for mineral and FYM treatments, respectively (Table 2). These values are 3- to 10-fold less than those reported for some irrigated croplands receiving high fertilizer N inputs (Ryden and Lund 1980). Present results, however, are consistent with those of earlier studies in which 1–5% loss of the applied fertilizer N has been reported under irrigated field conditions (Hallmark and Terry 1985; Mosier et al. 1986). The major cause for the low denitrification loss observed in the present study is that conditions of high soil moisture content, combined with an adequate supply of soil NO_3^--N, were restricted to only a few events during the growing season. Results of the present study indicate that denitrification is not an important N loss mechanism in this irrigated, well-drained soil under a wheat-maize cropping system receiving fertilizer inputs in the range of 100–200 kg N ha^{-1} year^{-1}. However, during the present study denitrification was measured only in the 0–15 cm layer of soil, taking no account of the processes in the deeper soil layers. Studies are in progress to quantify denitrification loss from irrigated wheat and maize fields with a working soil depth of 0–50 cm and to compare the directly measured denitrification loss with the total fertilizer N loss measured by ^{15}N-balance. Moreover, studies on the denitrification loss during the period of monsoon rains (July to August) are also in progress.

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