Pak. J. Soil Sci., Vol.19 : 41-50, 2001

DENITRIFICATION LOSS FROM IRRIGATED CROPLANDS IN THE FAISALABAD REGION – A REVIEW OF THE AVAILABLE DATA

Mahmood, T.*, F. Azam* and K. A. Malik***

ABSTRACT

Field measurements of nitrogen loss from irrigated croplands have been lacking under agroclimatic conditions in Pakistan. It is only recently that field studies on denitrification and total fertilizer N losses were reported from some irrigated croplands in the Faisalabad region. This paper reviews the available data on the directly measured denitrification loss from maize, wheat and cotton, and the fate of ^{15}N-labeled fertilizer applied to these crops under irrigated field conditions.

INTRODUCTION

Denitrification is an important mechanism of N loss from soil-plant systems and a major source of the atmospheric nitrous oxide (N_2O), which besides acting as a greenhouse gas (Watson *et al.* 1990), is implicated in the depletion of stratospheric ozone (Crutzen, 1981). Quantitative estimates of N losses through denitrification vary considerably and may range from < 1 to 200 kg ha^{-1} year^{-1} (Ryden and Lund, 1980; Myrold, 1988; Bertelsen and Jensen, 1992). Methods for the direct measurement of gaseous N products of denitrification are based on ^{15}N and acetylene inhibition (AI), the latter being used more commonly because of the lower cost and higher sensitivity (Ryden and Rolston, 1983). Soil cover (Ryden *et al.* 1979) and soil core (Ryden *et al.* 1987) versions of the AI technique have been widely used for the quantification of denitrification under field conditions with higher figures generally reported by the soil core method (Arah *et al.* 1991; Mahmood *et al.* 1998a). Denitrification can also be measured indirectly using ^{15}N-balance technique, assuming that the unaccounted for N is lost only through denitrification. Although, a close agreement was found between AI and ^{15}N-balance techniques (Aulakh *et al.* 1983) or between ^{15}N gaseous flux and ^{15}N-balance (Mosier *et al.* 1986), higher values by ^{15}N-balance than AI method have often been reported (Bertelsen and Jensen, 1992; Mahmood *et al.* 1998a). Overestimation of denitrification by ^{15}N-balance is partly attributed to underestimation by the AI technique (Mahmood *et al.* 1998a), and/or to other forms of losses, such as NH_3-volatilization and loss through plant parts (Farquhar *et al.* 1979; Nelson, 1982).

In Pakistan, crop husbandry largely depends on irrigation and other inputs including fertilizer N, the annual consumption of which stands at 2.01 × 10^6 t for 22.96 × 10^6 ha of cultivated land (MINFAL, 2000). Some laboratory studies carried out on soils of the Faisalabad region indicated that up to 30% of the total applied N may be lost through NH_3-volatilization (Hamid and Ahmad, 1987). Although, NH_3-volatilization is often envisaged as the major N loss process under alkaline calcareous soil conditions, field data on NH_3-volatilization and denitrification losses from Pakistani soils have generally been lacking. It has been only recently that field measurements of denitrifcation were reported from some irrigated croplands in the Faisalabad region. This paper

---

* *Soil Biology Division, Nuclear Institute for Agriculture and Biology, P.O. Box 128, Faisalabad.*

** *Present address: Pakistan Atomic Energy Commission, P.O. Box 1114, Islamabad.*

reviews the available information on the directly measured denitrification loss under maize, wheat and cotton. The fate of ^{15}N-labeled fertilizer applied to these crops under field conditions has also been discussed.

Measurement techniques

Different versions of the AI technique were employed for the direct measurement of denitrification under field conditions. The technique is based on the observation that nitrous oxide reduction into dinitrogen is inhibited by small (≥0.1% v/v) amounts of acetylene. The sole product of denitrification in the presence of acetylene i.e. nitrous oxide can be measured even in ppb amounts employing gas chromatography with electron-capture detector. Three different versions of the AI technique were employed, viz., AI-soil cover method (Ryden *et al.*, 1979), AI-soil core method (Ryden *et al.*, 1987) and AI-soil core method modified to include the N_2O entrapped in soil (Rice and Smith, 1982). Details of the AI technique have been described elsewhere (Mahmood *et al.*, 1998a, 1998b, 1999a, 2000). Fate of the applied fertilizer-N was studied by the ^{15}N-balance technique (Mahmood *et al.*, 1998a, 2000) and these experiments were concurrent to the denitrification measurements. The ^{15}N microplots consisted of PVC pipes pushed to a depth of 1 m within the main fields. Fertilizer and irrigation regimes for the ^{15}N microplots were similar to those for the surrounding field used for measuring denitrification except that ^{15}N-labeled ammonium sulphate (for maize and wheat) or urea (for cotton) were applied.

Denitrification loss under maize

Denitrification loss from maize field was quantified by AI-soil cover method with a working soil depth of 50 cm. The site has been under irrigated maize receiving urea-N at 100 kg N ha^{-1} for the past 10 years. Total denitrification loss during the growing season (24 August to 26 October) was 2.7 kg N ha^{-1} (Mahmood *et al.* 1998a). Most (87%) of the denitrification loss occurred during the first two irrigation cycles (Table 1). Peaks of denitrification were recorded 12 hour after irrigation, followed by a gradual decline to background levels within 5–7 days. Peaks during the first two irrigation cycles (23–27 g N ha^{-1} h^{-1}) coincided with those of NO_3^--N and were 7–14 times higher than those recorded during the last two irrigation cycles.

Table 1. **Denitrification loss integrated over different irrigation cycles under maize.**[a]

Irrigation applied (mm)	Measurement period	Denitrification loss (kg N ha^{-1})[b]
100	24 Aug–14 Sep	1.15 ± 0.35
75	23 Sep–6 Oct	1.21 ± 0.60
75	7–14 Oct	0.22 ± 0.08
75	21–26 Oct	0.14 ± 0.05
	Season total	2.72 ± 1.09

[a] *Source, Mahmood* et al. *(1998a); denitrification rate measured by the acetylene inhibition-soil cover method; the maize field received urea-N at 100 kg N ha^{-1}.*

[b] *All values are mean of four replicates ± SD.*

Denitrification loss under wheat

The study site under wheat received urea-N at 100 kg N ha^{-1} for the past 10 years. Two versions of the AI technique viz. soil cover and soil core were compared for measuring denitrification with a working soil depth of 50 cm. Denitrification loss during the wheat growing season (22 November to 20 April) was only 1.1 and 3.4 kg N ha^{-1} by soil cover and soil core methods, respectively and most (70–88%) of this loss occurred during the first three irrigation cycles (Table 2). Further experiments revealed that the soil cover method underestimated denitrification loss of N because of the incomplete recovery of the N_2O produced under the acetylene-treated site due to its downward movement from the site of production (Mahmood *et al.* 1998a). Secondly, lateral movement of denitrification-N_2O from the site of production might also contribute to the underestimation by soil cover method.

Table 2. **Denitrification loss integrated over different irrigation cycles under wheat.**[a]

Irrigation applied (mm)	Measurement period	Denitrification loss (kg N ha^{-1})	
		Soil cover method[b]	Soil core method[c]
100	22 Nov–10 Jan	0.29 ± 0.18	0.88 ± 0.37
75	11–28 Jan	0.25 ± 0.10	0.70 ± 0.19
75	9 Feb–2 Mar	0.26 ± 0.04	1.41 ± 0.36
75	10–23 Mar	0.08 ± 0.02	0.20 ± 0.10
75	1–8 Apr	0.11 ± 0.02	0.05 ± 0.04
75	13–20 Apr	0.16 ± 0.12	0.16 ± 0.05
	Season total	1.14 ± 0.47	3.39 ± 1.11

[a] *Source, Mahmood* et al. *(1998b); the crop received urea-N at 100 kg N ha^{-1}.*

[b] *Acetylene inhibition-soil cover method; all values are mean of four replicates ± SD.*

[c] *Acetylene inhibition-soil core method; all values are mean of fifteen replicates ± SD.*

Effect of fertilizer treatments on denitrification

Effect of fertilizer treatments on denitrification was investigated under wheat-maize cropping system receiving five fertilizer treatments for the past years (Mahmood *et al.* 1998b). Treatments included: N-100, (urea-N at 100 kg N ha^{-1} year^{-1}), N-200 (urea-N at 200 kg N 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). In urea treatments, half of the urea was applied to each crop, whereas all the FYM was applied at wheat sowing. In this study, denitrification was quantified by Al-soil core method with a working soil depth of 15 cm. Denitrification loss integrated over the whole vegetation period was at 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 minimum (5.8 kg N ha^{-1}) was recorded under the control (Table 3). However, in general, treatment effects were statistically non-significant due to high degree of spatial variability.

Effect of plants on denitrification

The study was conducted to examine the effect of maize plants on denitrification under irrigated field conditions (Mahmood *et al.* 1997). Both planted and unplanted plots received urea-N at 150 kg N ha^{-1}. In a third treatment, which was also planted and received urea-N at 150 kg N ha^{-1}, the soil NO_3^--N was equalized to that in the unplanted plot by applying $Ca(NO_3)_2$. Although, maize plants always showed the potential to increase denitrification as revealed by different carbon availability indices, presence of plants generally decreased actual denitrification rate by limiting the supply of NO_3^- for denitrifiers (Table 4). However, when NO_3^--N uptake by plants was compensated through additional doses of $Ca(NO_3)_2$, denitrification rate was always higher in the presence of plants (Table 4). The effect of plants on denitrification and related parameters was confined to the root zone (Table 5). The major implication of this study is that, cropped fields should be sampled both from planted as well as unplanted portions in order to obtain reliable assessment of denitrification.

Underestimation of denitrification

In experiments with wheat-maize cropping system (Mahmood *et al.* 1998a), there was an indication that both soil cover and soil core methods underestimated denitrification because of diffusion constraints. With the soil cover method, all the denitrification-N_2O is not collected as it may also move laterally and perhaps downward from the site of its production. With the soil core method, all the denitrification-N_2O is not released into the headspace of incubation vessels, as a significant proportion may remain entrapped within the soil cores. In a field experiment, N_2O entrapment was investigated using the Al-soil core technique. The experimental site was cropped to wheat, but had been under cotton for the past 20 years. Because of regular inputs of cotton crop residues and urea-N, the fertility level of the experimental plot was much higher than that used for wheat-maize cropping system. Of the total denitrification-N_2O produced, 4–75% (average, 36%) remained entrapped in the soil cores at the end of incubation (Mahmood *et al.* 1999a). Taking into account the N_2O released from soil cores and that entrapped in the soil, total denitrification loss during the wheat-growing period (29 November to 7 April) was 18.8 kg N ha^{-1} (Table 6). In contrast, a loss of 9.8 kg N ha^{-1} was recorded by the conventional soil core method, as the entrapped N_2O was not taken into account. Consequently, all the previous data for wheat-maize cropping system was corrected for the entrapped N_2O (Table 7).

Denitrification loss under cotton

The study site under cotton has been receiving urea-N at 158–173 kg N ha^{-1} year^{-1} in addition to all the cotton crop residues, which have been regularly incorporated for the past 20 years. Acetylene inhibition-soil core method was employed for measuring denitrification, taking into account the N_2O released from soil cores as well as that entrapped in the soil. A total of 65.7 and 64.4 kg N ha^{-1} was lost due to denitrification from cotton field during 1995 and 1996 growing season, respectively (Mahmood *et al.* 2000). Most (>70%) of the denitrification loss occurred during June-August, the period characterized by high soil temperatures and heavy monsoon rains (Table 8). Higher denitrification loss under cotton may be attributed to higher availability of carbon and NO_3^-. Besides, the warm and humid climate during cotton growing period was also more conducive to denitrification as compared to wheat-maize cropping system in which denitrification measurements were not made during the monsoon fallow period.

Table 3. **Denitrification loss (kg N ha^{-1}) under wheat and maize integrated over each irrigation cycle and for the whole crop periods (see text for explanation of treatments)[a]**

Crop	Irrigation (mm)	Measurement period	Fertilizer treatment				
			N-100	N-200	FYM-16	FYM-32	Control
			------------- Denitrification loss (kg N ha^{-1}) -------------				
Wheat	100	15–28 Nov	0.72 b	1.36 a	0.60 b	1.49 a	0.59 b
	75	27 Dec–7 Jan	1.33 a	1.76 a	1.28 a	1.22 a	0.83 b
	75	14–18 Feb	0.08 ab	0.15 a	0.01 c	0.04 bc	0.01 c
	75	1–5 Mar	0.01 bc	0.04 a	0.01 b	0.01 b	0.00 c
	50	19–24 Mar	0.02 a	0.02 a	0.06 a	0.09 a	0.02 a
	75	3–14 Apr	0.29 ab	0.61 a	0.20 ab	0.31 a	0.06 b
		Season total	*2.44 b*	*3.94 a*	*2.15 bc*	*3.15 ab*	*1.51 c*
Maize	100	22 Aug–6 Sep	2.10 bc	2.83 b	4.50 a	4.64 a	1.90 c
	75	13–17 Sep	0.42 c	0.91 bc	1.89 ab	3.47 a	1.03 bc
	75	27 Sep–9 Oct	2.47 a	2.81 a	1.84 a	2.23 a	1.13 b
	75	10–15 Oct	0.53 b	1.29 a	0.23 bc	0.37 b	0.17 c
	50	21–31 Oct	0.04 a	0.04 a	0.03 a	0.05 a	0.02 a
		Season 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*

[a] *Source, Mahmood* et al. *(1998b); acetylene inhibition-soil core method employed for measurement of denitrification rate without considering the entrapped N_2O; values within rows followed by different letter are significantly different at* $p < 0.05$.

Table 4. **Carbon availability and NO_3^--N content of the field soil, and denitrification rate in the field with and without maize plants.[a]**

Parameter	Treatment		
	Planted	Unplanted	Planted+NO_3^-
Aerobically mineralizable C (µg g^{-1})	129 a	82 b	124 a
Soil respiration rate (kg C ha^{-1} d^{-1})	21.1 a	6.8 b	21.4 a
Microbial biomass carrying capacity (µg C g^{-1})	339 a	254 b	330 a
Denitrification potential (ng N g^{-1} h^{-1})	556 a	274 b	524 a
Soil NO_3^- (µg N g^{-1})	5.9 b	9.4 a	10.8 a
Denitrification rate (g N ha^{-1} d^{-1})	162 c	343 b	1153 a

[a] *Source, Mahmood* et al. *(1997); acetylene inhibition-soil core method employed for measurement of denitrification rate without considering the entrapped N_2O; all values are average of 10 sampling dates over the maize growing season; within each row, values followed by different letter are significantly different at* $p < 0.05$.

Table 5. **Effect of distance from maize plants on denitrification and related parameters.**

Parameter	Distance from plant (cm)		
	0	15	30
Denitrification rate (g N ha^{-1} d^{-1})	330 b	707 a	1007 a
Soil NO_3^- (µg N g^{-1})	1.5 b	2.8 a	2.8 a
Water-filled pore space (%)	77 a	79 a	78 a
Aerobically mineralizable C (µg g^{-1})	239 a	162 b	154 b
Soil respiration rate (kg C ha^{-1} d^{-1})	9.6 a	6.5 b	6.2 b
Microbial biomass carrying capacity (µg C g^{-1})	373 a	284 b	283 b
Denitrification potential (ng N g^{-1} h^{-1})	365 a	216 b	178 b

[a] *Source, Mahmood* et al. *(1997); investigated 24 h after irrigation on 38 days after germination; within each row, values followed by different letter are significantly different at* $p < 0.05$.

Table 6. **Denitrification loss during different irrigation cycles under wheat as measured by two versions of the acetylene inhibition-soil core method.**[a]

Event	Measurement period	Denitrification loss (kg N ha^{-1})[b]	
		Soil core method-A[c]	Soil core method-B[d]
1. Irrigation (100 mm)	29 Nov–14 Dec	0.12 ± 0.15	0.28 ± 0.27
2. Irrigation (75 mm)	4–22 Jan	3.90 ± 2.45	8.78 ± 7.05
3. Rainfall	11–13 Feb	0.53 ± 0.97	1.38 ± 2.01
4. Irrigation (50 mm)	14 Feb–7 Mar	3.09 ± 2.85	4.23 ± 3.43
5. Irrigation (75 mm)	12–16 Mar	0.74 ± 0.58	1.61 ± 1.36
6. Rainfall	17–27 Mar	1.21 ± 0.99	2.12 ± 1.60
7. Irrigation (75 mm)	4–7 Apr	0.25 ± 0.23	0.42 ± 0.32
	Season total	*9.84 ± 8.22*	*18.82 ± 16.08*

[a] *Source, Mahmood* et al. *(1999a); the crop received urea-N at 100 kg N ha^{-1} in two equal splits, one at sowing and the other with the 2nd irrigation.*

[b] *All values are mean of fifteen replicates ± SD.*

[c] *Acetylene inhibition-soil core method-A, denitrification rate estimated by head space N$_2$O analysis followed by calculation of the N$_2$O dissolved in the solution phase using Bunsen absorption coefficients (Ryden* et al. *1987).*

[d] *Acetylene inhibition-soil core method-B, denitrification rate measured by head space N$_2$O analysis followed by analysis of the entrapped N$_2$O released by shaking soil cores with excess water (Rice and Smith, 1982).*

Table 7. **Corrected values for the denitrification loss (kg N ha^{-1}) under wheat-maize cropping system receiving different N fertilizer treatments.**[a]

Crop	Fertilizer treatment				
	N-100	N-200	FYM-16	FYM-32	Control
Wheat	4.67 b	7.54 a	4.11 bc	6.02 ab	2.89 c
Maize	10.60 bc	14.99 ab	16.24 a	20.58 a	8.13 c
Both crops total	15.26 bc	22.59 a	20.35 ab	26.60 a	11.02 c

[a] *Data in Table 3 corrected for the entrapped N$_2$O using the relationship between the soil core methods A and B in Table 6; values within rows followed by different letter are significantly different at* $p < 0.05$.

Table 8. **Denitrification loss integrated over different irrigation/rainfall cycles under cotton.**[a]

Growing-season	Event	Measurement period	Denitrification loss (kg N ha^{-1})
1995	1. Irrigation (100 mm)	15-23 May	10.45
	2. Rainfall (128 mm)	20-27 June	8.02
	3. Irrigation (75 mm)	6-10 July	1.94
	4. Rainfall (293 mm)	14 July-29 Aug	36.06
	5. Irrigation (75 mm)	8-14 Sep	1.87
	6. Irrigation (75 mm)	19-25 Sep	2.48
	7. Irrigation (75 mm)	5-11 Oct	2.78
	8. Irrigation (75 mm)	26 Oct-5 Nov	1.15
		Season total	*65.65*
1996	1. Irrigation+Rainfall (50+6 mm)	12-20 May	1.20
	2. Irrigation+Rainfall (100+7 mm)	21-26 May	3.48
	3. Rainfall (163 mm)	13 June-2 July	17.66
	4. Irrigation (75 mm)	16-20 July	19.59
	5. Rianfall (60 mm)	22 July-7 Aug	5.69
	6. Irrigation+Rainfall (75+58 mm)	13-19 Aug	7.89
	7. Irrigation+Rainfall (75+23 mm)	6-12 Sep	5.35
	8. Irrigation+Rainfall (75+16 mm)	19-25 Sep	2.02
	9. Irrigation (75 mm)	2-8 Oct	0.78
	10. Irrigation (75 mm)	17-23 Oct	0.76
		Season total	*64.42*

[a] *Source, Mahmood* et al. *(2000); urea-N applied during 1995 and 1996 growing seasons was 158 and 173 kg ha^{-1}, respectively; acetylene inhibition/soil core method was used and the denitrification rate was measured by analysis of the head space N$_2$O and the N$_2$O entrapped in the soil cores released after shaking the soil with excess water; average CV was 71% and 61% during 1995 and 1996 growing seasons, respectively.*

Factors controlling denitrification

Under wheat-maize cropping system, major soil factors governing denitrification were water-filled pore space [WFPS, (r = 0.495, $p < 0.001$)], NO_3^--N content (r = 0.519, $p < 0.001$) and temperature (r = 0.261, $p < 0.001$). Since denitrification rates measured under field conditions were always much lower than the denitrification potential of the field soil (Mahmood *et al.* 1999b), in this particular system the process does not seem to be limited by the supply of carbon as energy source for denitrifiers. Therefore, higher denitrification rates recorded under FYM treatments (Mahmood *et al.* 1998b) may be attributed to the indirect effect of FYM-carbon, i.e. promotion of anoxic microsites rather than its direct role as energy source.

Denitrification rates under cotton were significantly correlated with WFPS (r = 0.531, $p < 0.001$) and soil respiration rate (r = 0.464, $p < 0.001$), but not with the soil NO_3^--N level or soil temperature (Mahmood *et al.* 2000). The stimulatory effect of soil respiration may be attributed to the development of anoxic microsites rather than direct effect of soil carbon as energy source for denitrifiers. This was evidenced from denitrification potential of the cotton field soil that was always several-fold higher than the actual denitrification rates recorded in the field. The effect of soil temperature on denitrification was masked during the cotton season, though denitrification peaks following irrigation or rainfall events were significantly correlated with the soil temperature (r = 0.541, $p < 0.01$). The lack of relationship between denitrification rate and soil NO_3^--N indicates that, in this particular system, the process was not limited by the supply of NO_3^--N.

Fate of the applied fertilizer-N (^{15}N-balance)

During the maize growing season (1 September to 31 October), 37.3% of the applied N was utilized by the crop and 23.5% was recovered in soil. During the wheat-growing season (9 December to 6 May), 39.2% of the applied N was recovered in crop whereas 27.7% remained in the soil at harvest. Total fertilizer N loss during the maize and wheat was 39.2% and 33.1%, respectively (Table 9), which is several-fold higher than the denitrification loss directly measured by the AI technique (Mahmood *et al.* 1998a). The discrepancy may partly be attributed to losses other than denitrification, most probably NH_3-volatilization, and/or to underestimation of denitrification by the AI technique. Table 10 shows the fertilizer-N balance sheet for the 1996 cotton-growing season. Of the total fertilizer-N applied, 39.3% was utilized by the crop and 19.2% remained in the soil at harvest. Most (77%) of the fertilizer-N used by the crop was recovered in shoot component, followed by seed (19%) and roots (4%). At harvest, most (97%) of the residual fertilizer N in the soil was present in the organic form and maximum (74%) was recovered in the upper 30 cm. Comparing the directly measured denitrification loss (64.4 kg N ha^{-1}) with the concurrently measured N-balance loss (71.8 kg N ha^{-1}, Mahmood *et al.* 2000), the two figures may not be statistically different because of high spatial variability recorded for denitrification. Since ^{15}N-balance measures the N loss only from the applied N fertilizer, and takes no account of the loss from the native soil N pool. Therefore, considering also the N lost from the native soil N pool, total N loss under maize, wheat and cotton fields might be higher than the values recorded with ^{15}N-balance technique.

Nitrogen loss as nitrous oxide

Since denitrification is a major source of the atmospheric N_2O, studies were also conducted to quantify N_2O emissions from irrigated field conditions. These measurements were concurrent to the denitrification measurements from maize and wheat fields. The continuous-flow soil cover method of Ryden *et al.* (1978) was employed to quantify N_2O emissions. Total N_2O emissions during the growing period of maize and wheat were low (Table 11) and amounted to 0.16 and 0.49 kg N ha^{-1} (Mahmood *et al.* 1998c). A major reason for the low N_2O emissions may be the overall low denitrification loss under maize and wheat (Mahmood *et al.* 1998a). Reduced diffusion of N_2O from the soil and its subsequent reduction to N_2 might be another reason for the observed low N_2O emissions under these crops. Gas diffusion might have been reduced as a result of damage to the structure of the surface layer following flood-irrigation that is known to cause surface crust and a decrease in the aggregate stability (Terry *et al.* 1986). The generally low proportion of N_2O in the gaseous N products of denitrification and the frequently observed negative N_2O fluxes indicated that, the soil conditions under irrigated maize and wheat were favourable for N_2O reduction. Some unpublished data from irrigated cotton fields at NIAB further confirm that under agroclimatic conditions prevailing in this region, dinitrogen is the major end product of denitrification and N_2O emission is of minor significance.

Table 9. Fertilizer nitrogen balance sheets for the maize and wheat growing seasons.[a]

Component	Maize fodder	Wheat
	---------- % of the applied fertilizer-N ----------	
Recovery in plant		
Grain	–	17.47 ± 2.89
Shoot	35.97 ± 2.50	20.08 ± 1.61
Root	1.35 ± 0.11	1.66 ± 0.42
Recovery in soil (depth cm)		
0–10	13.50 ± 1.75	16.32 ± 1.84
10–20	5.38 ± 2.02	3.07 ± 0.47
20–30	2.10 ± 1.26	2.76 ± 1.16
30–40	0.87 ± 0.07	2.02 ± 0.83
40–50	0.39 ± 0.12	0.97 ± 0.19
50–100	1.27 ± 0.68	2.59 ± 0.47
Total recovery (plant + soil)	*60.82 ± 4.10*	*66.94 ± 1.97*
Loss	*39.18 ± 4.10*	*33.06 ± 1.97*

[a] *Source, Mahmood* et al. *(1998a); each crop received ammonium sulphate at 100 kg N ha^{-1} with 31.7 atom% ^{15}N; all values are mean of three replicates ± SD.*

Table 10. Fertilizer-nitrogen balance sheet for the 1996 cotton growing season.[a]

Component	% of the applied N[b]
Recovery in plant	
Seed	7.57 ± 3.70
Shoot	30.25 ± 2.93
Root	1.48 ± 0.42
Recovery in soil *(depth cm)*	
0–10	10.03 ± 1.49 (0.17 ± 0.02)
10–20	2.99 ± 0.85 (0.07 ± 0.01)
20–30	1.21 ± 0.20 (0.04 ± 0.01)
30–40	1.01 ± 0.23 (0.03 ± 0.01)
40–60	1.51 ± 0.29 (0.09 ± 0.04)
60–80	1.46 ± 0.33 (0.06 ± 0.05)
80–100	0.95 ± 0.40 (0.08 ± 0.04)
Total recovery (plant + soil)	*58.47 ± 4.06*
Loss	*41.53 ± 4.06*

[a] *Source, Mahmood* et al. *(1999b); all values are mean of four replicates ± SD.*

[b] *The crop received urea at 173 kg N ha^{-1} with 25.06 atom% ^{15}N.*

[c] *Figures in parentheses represent the fertilizer-N present in the mineral form.*

Table 11. Nitrous oxide emissions integrated over different irrigation cycles under maize and wheat.[a]

Crop[b]	Irrigation applied (mm)	Measurement period	N_2O emission (kg N ha^{-1})[c]
Maize	100	24 Aug–14 Sep	0.13 ± 0.06
	75	23 Sep–6 Oct	0.07 ± 0.10
	75	7–14 Oct	– 0.02 ± 0.01
	75	21–26 Oct	– 0.02 ± 0.02
		Season total	*0.16* ± 0.13
Wheat	100	22 Nov–10 Jan	0.01 ± 0.01
	75	11–28 Jan	0.50 ± 0.16
	75	9 Feb–2 Mar	0.03 ± 0.03
	75	10–23 Mar	– 0.04 ± 0.04
	75	1–8 Apr	0.01 ± 0.04
	75	13–20 Apr	– 0.02 ± 0.02
		Season total	*0.49* ± 0.18

[a] *Source, Mahmood* et al. *(1998c).*

[b] *Each crop received urea-N at 100 kg N ha^{-1}.*

[c] *All values are mean of four replicates ± SD; negative values indicate the N_2O sink activity.*

CONCLUSIONS

Under agroclimatic conditions prevailing in the central Punjab region, denitrification loss was low (8 kg N ha^{-1}) from wheat field receiving urea-N at 100 kg N ha^{-1} for the past 10 years. However, when wheat was planted in a relatively fertile field that received cotton crop residues for the past 20 years, denitrification loss was higher and amounted 19 kg N ha^{-1}. Significant denitrification loss was recorded during the growing season of maize that amounted 15 kg N ha^{-1} when the crop was fertilized with urea at 100 kg N ha^{-1}. Moreover, significant denitrification loss may also be expected during the monsoon fallow period between wheat and maize crops and needs to be quantified. In contrast to wheat-maize cropping system, denitrification loss was as high as 66 kg N ha^{-1} in a cotton field that regularly received crop residues in addition to 158–173 kg N ha^{-1} of urea-N. Most of the denitrification loss under cotton was recorded during June-August, the period during which the crop is exposed to high summer temperatures and heavy monsoon downpours. Total fertilizer-N loss from wheat, maize and cotton was always high and ranged from 33 to 42% of the applied N. This is important to mention that the ^{15}N-balance measures the loss only from the applied N fertilizer, taking no account of the loss from the native soil N pool. Therefore, considering also the N loss from the native soil N pool, total N loss under these crops might be higher than that recorded with the ^{15}N-balance technique. Nevertheless, the available data emphasize that a substantial proportion of the fertilizer-N applied to irrigated croplands is lost under semiarid subtropical climatic conditions prevailing in the central Punjab region. Denitrification is an important N loss process particularly under irrigated cotton and appropriate strategies need to be adopted to reduce this loss. Results obtained warrant field measurement of N loss from other cropping systems, such as rice and sugarcane. A considerable amount of NO_3^--N may accumulate during the fallow periods between different crops and may lead to significant denitrification loss, particularly during the monsoon period. Such losses also need to be quantified in order to obtain more representative assessment of denitrification loss. Besides, relative significance of denitrification and NH_3-volatilization as the N loss processes is also poorly understood under agroclimatic conditions in this region. This is because quantitative estimates of NH_3-volatilization under field conditions in Pakistan are almost lacking. The available data mostly pertain to laboratory conditions. The process of NH_3-volatilization is strongly influenced by factors, such as evaporation rate, temperature, wind speed, ambient NH_3 concentration, and even dew formation

(Denmeade, 1983). Therefore, the data obtained under laboratory conditions need to be validated under field conditions. In this regard, micrometeorological methods (Denmeade, 1983) may serve as useful tools for the quantification of NH_3-volatilization under field conditions. Since different technological approaches are required to be adopted to reduce denitrification and NH_3-volatilization losses, it is imperative to have reliable field data on different N loss mechanisms.

REFERENCES

Arah, J.R.M., K.A. Smith, I.J. Crichton, and H.S. Li. 1991. Nitrous oxide production and denitrification in Scottish arable soils. J. Soil Sci. 42: 351-367.

Aulakh, M.S., D.A. Rennie, and E.A. Paul. 1983. Field studies on gaseous nitrogen losses from soils under continuous wheat versus a wheat-fallow rotation. Plant and Soil 75:15!27

Bertelsen, F, and E.S. Jensen. 1992. Gaseous nitrogen losses from field plots grown with pea (*Pisum sativum* L.) or spring barley (*Hordeum vulgare* L.) estimated by ^{15}N mass balance and acetylene inhibition techniques. Plant and Soil 142: 287-295.

Crutzen, P.J. 1981. Atmospheric chemical processes of the oxides of nitrogen, including nitrous oxide. *In:* Denitrification, nitrification and atmospheric nitrous oxide. John Wiley and Sons, New York. pp 17-44.

Denmeade OT (1983) Micrometeorological methods for measuring gaseous losses of nitrogen in the field. *In*: Gaseous Loss of Nitrogen from Plant-Soil systems. J R Freney and J R Simpson (eds.) Nijhoff/Junk. The Hague. pp 133-157.

Farquhar, G.D., R. Wetselaar, and P.M. Firth. 1979. Ammonia volatilization from senescing leaves of maize. Science 203: 1257!1258.

Hamid, A and M. Ahmad. 1987. Ammonia volatilization losses from nitrogen fertilizers in alluvial alkaline soils. Pak. J. Agric. Sci. 24: 129-139.

Mahmood, T, R. Ali, K.A. Malik, and S.R.A. Shamsi. 1997. Denitrification with and without maize plants (*Zea mays* L.) under irrigated field conditions. Biol. Fertil. Soils 24: 323-328.

Mahmood, T. K.A. Malik, S.R.A. Shamsi, and M.I. Sajjad. 1998a. Denitrification and total N losses from an irrigated sandy-clay loam under maize-wheat cropping system. Plant and Soil 199: 239-250.

Mahmood, T. G.R. Tahir. K.A. Malik, and S.R.A. Shamsi. 1998b. Denitrification losses from an irrigated sandy-clay loam under a wheat-maize cropping system receiving different fertilizer treatments. Biol. Fertil. Soils 26: 35-42.

Mahmood, T., R. Ali, K.A. Malik, and S.R.A. Shamsi. 1998c. Nitrous oxide emissions from an irrigated sandy-clay loam cropped to maize and wheat. Biol. Fertil. Soils 27: 189-196.

Mahmood, T., R. Ali, K.A. Malik, and F. Azam. 1999a. Comparison of two versions of the acetylene inhibition-soil core method for measuring denitrification loss from an irrigated wheat field. Biol. Fertil. Soils 29:328-331

Mahmood, T., A.S. Bhatti, and K.A. Malik (1999b). Seasonal changes in denitrification potential of an irrigated sandy-clay loam under a wheat-maize cropping system receiving different fertilizer treatments. Pak J Biol Ssci 2:1451-1454.

Mahmood, T., R. Ali, M.I. Sajjad, M.B. Chaudhri, G.R. Tahir, and F. Azam. (2000). Denitrification and total fertilizer N losses from an irrigated cotton field. Biol. Fertil. Soils 31:270-278.

MINFAL. 2000. Agricultural statistics of Pakistan. Government of Pakistan 1998-99. Ministry of Food, Agriculture and Livestock (Economic Wing), Islamabad, Pakistan.

Mosier, A. R., W.D. Guenzi, and E.E. Scheweizer. 1986. Soil losses of dinitrogen and nitrous oxide from irrigated crops in North-eastern Colorado. Soil Sci. Soc. Am. J. 50: 344!348.

Myrold, D. D. 1988. Denitrification in ryegrass and winter wheat cropping systems of Western Oregon. Soil Sci. Soc. Am. J. 52: 412!416.

Nelson, D.W. 1982. Gaseous Losses of nitrogen other than through denitrification. *In*: F.J. Stevenson (ed.) Nitrogen in Agricultural Soils, Agronomy Monograph 22, American Society of Agronomy, Madison, Wisconsin, pp 327-363.

Rice, C. W., and M.S. Smith. 1982. Denitrification in no-till and plowed soils. Soil Sci. Soc. Am. J. 46: 1168!1173.

Ryden, J. C., and L.J. Lund. 1980. Nature and extent of directly measured denitrification losses from some irrigated vegetable crop production units. Soil Sci. Soc. Am. J. 44: 505!511.

Ryden, J.C., L.J. Lund, and D.D. Focht. 1978. Direct in-field measurement of nitrous oxide flux from soils. Soil Sci. Soc. Am. J. 42: 731-737.

Ryden, J. C., L.J. Lund, J. Latey, and D.D. Focht. 1979. Direct measurement of denitrification loss from soils. II. development and application of field methods. Soil Sci. Soc. Am. J. 43: 110-118.

Ryden, J. C., and D.E. Rolston. 1983. The measurement of denitrification. *In*: Gaseous Loss of Nitrogen from Plant-Soil systems. J R Freney and J R Simpson (eds.) Nijhoff/Junk. The Hague. pp 91-132.

Ryden, J. C., J.H. Skinner, and D.J. Nixon. 1987. Soil core incubation system for the field measurement of denitrification using acetylene-inhibition. Soil Biol. Biochem. 19: 753!757.

Terry, R.E., E.N. Jellen, and D.P. Breakwell. 1986. Effect of irrigation methods and acetylene exposure on field denitrification measurements. Soil Sci. Soc. Am. J. 50: 115-120.

Watson, R.T., H. Rodhe, H. Oeschger, and U. Siegenthaler. 1990. Greenhouse gases and aerosols. *In*: Climate change: The IPCC Scientific Assessment. J.T. Houghton, G.S. Jenkins, and J.J. Ephraums (eds). Cambridge University Press, Cambridge, pp 1-40.