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Lysimeter studies on recovery of ^{15}N-labeled urea in wetland rice

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Summary Results of a two year study on the fate on ^{15}N-labelled urea (9.95 atoms percent excess ^{15}N) applied @ 180 kg N/ha to flooded rice in monolith lysimeters at the Punjab Agricultural University Farm, Ludhiana are reported. The soil of the experimental field was sandy clay loam in texture (Typic Ustochrept), had pH 7.9, organic carbon 0.36 percent, available N 187 kg/ha and total N 0.08 percent. The results revealed that 18.1 to 53.0 per cent of the fertilizer N was utilized by the rice plant, 25.1 to 41.1 percent was immobilized in the soil and 4.8 to 7.2 percent was lost by denitrification. The losses due to ammonia volatilization and leaching were negligible. The data on vertical distribution of labelled N in the soil profile reflected a higher concentration (38.3 to 39.5 per cent) in the surface (0–30 cm) soil. The content sharply decreased (1.8 to 2.4 percent) in lower soil layers (30–150 cm). A balance sheet of the various pathways of applied N showed that 58.8 to 72.2 and 66.2 to 83.0 percent N was recovered in 1976 and 1977, respectively and 17 to 41.2 per cent of labelled N still remained unaccounted for. Utilization of fertilizer N by rice was increased and losses decreased when N was applied in three equal splits as compared to the single N application at transplanting.

Availability of fertilizer N immobilized in the soil was investigated in the succeeding crops of wheat and rice. The results showed that 2.1 tot 3.4 per cent of the N applied to the preceding rice was utilized by the second rice crop grown in succession. This may look small but cannot be neglected on a long term basis. But there is need to initiate long term studies to investigate the turnover of residual N and to determine the fate of applied N in varying soil and cropping systems by using improved techniques.

Introduction

Among all the nutrients, crop responses to N application in Indian soils are universal. Rice is highly responsive to N application and is a major consumer of fertilizer N in the country. But the efficiency of N utilization in rice culture is notoriously low as compared to upland crop cultivation. Hauck[10] concluded from a review of the world literature that efficiency of applied N in rice was 25 to 45 per cent as compared to 50 to 70 per cent in upland crops. Limited work done in India with ^{15}N-labelled fertilizers show that fertilizer N utilization by rice seldom exceeded 30 to 40 per cent[8,13,32].

Fertilizer N on addition to flooded rice undergoes various types of reactions and transformations which tend to favour N losses through ammonia volatilisation[20,33,34] denitrification[15,16,22,31] and leaching[13]. A considerable portion of the applied N gets immobilized in the soil[5,15,16]. The magnitude of these losses may vary in varying rice ecosystems and needs investigation. The work on ^{15}N recovery in rice culture so far done in India and elsewhere has been mostly restricted to laboratory and green house conditions which are distinctly different from the evironment in the field. In any programme designed to increase the efficiency of applied N, quantitative data on the pathways of N loss under various rice ecosystems is important. The present study was undertaken to prepare a balance sheet of applied ^{15}N-labelled urea in rice culture and to measure the residual availability to the succeeding crops of fertilizer N immobilized or fixed by clay minerals in the soil.

Materials and methods

To study the fate of applied fertilizer N, a lysimeter experiment was conducted on a sandy clay loam soil (Typic Ustochrept) at the Punjab Agricultural University Farm, Ludhiana. The soil of the experimental field was non-saline and had pH 7.9. It was low in organic carbon (0.36%), available-N[30] (187 kg/ha), and medium in available P (16.7 kg/ha) and K (269 kg/ha).

The cylindrical lysimeters were made of steel and measured 165 cm long and 30 cm in diameter. The lysimeters were lowered into the soil by gentle hammering to a depth of 150 cm. The *in situ* soil-filled lysimeters were lifted and sealed from the bottom. A suitable size pit was dug in the field and the monolith lysimeters were placed to provide field growing conditions.

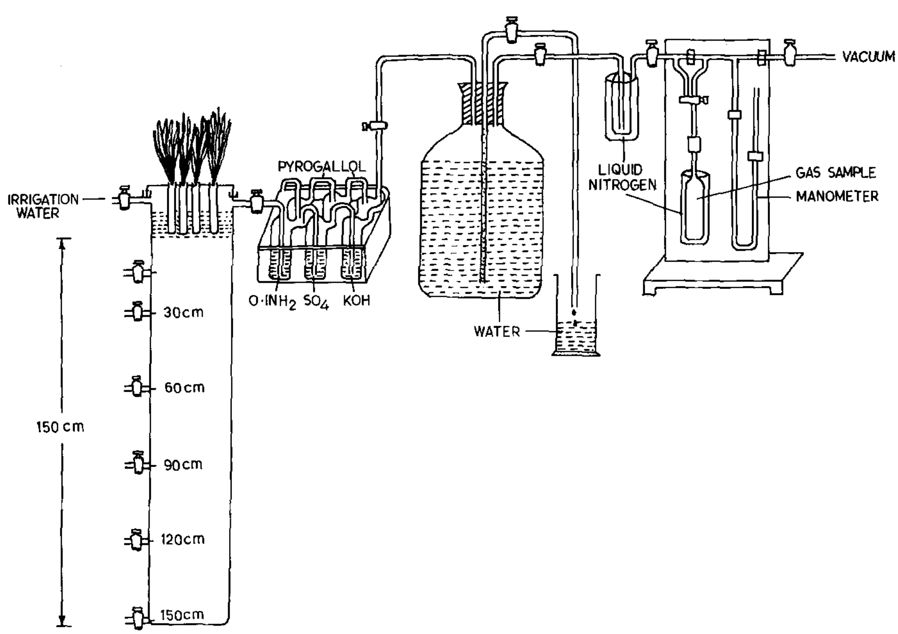

Fig. 1. Technique for the N balance sheet study.

The ^{15}N-labelled urea (9.95 atoms percent excess) at the rate of 180 kg N/ha was applied to rice grown in the lysimeters and the effect of the following treatments on N-recovery in the soil-plant system was studied: 1. No Nitrogen (check); 2. All N incorporated in surface 0–5 cm at transplanting; 3. $\frac{1}{3}$ N incorporated in surface 0–5 cm at transplanting, $\frac{1}{3}$ N applied at 3 weeks and the remaining $\frac{1}{3}$ N at 6 weeks after transplanting by broacasting into water.

A basal dose of 26 kg P and 28 kg K/ha was applied. Requisite quantity of water was added to puddle the soil and a waterhead of 5 cm was maintained in each lysimeter. The experiment was repeated in 1977 with the above treatments in the same lysimeters.

Rice variety PR–103 was used as indicator crop. Forty five and 35 days old rice seedlings were transplanted on 8 August and 30 July and harvested on 28th October and 25th October in 1976 and 1977 respectively. The grain and straw yield was recorded and samples collected for relevant analysis. Soil samples were collected from 0–15, 15–30, 30–60, 60–90, 90–120 and 120–150 cm depths to study the fertilizer N retained in the soil profile. The plant and soil samples were processed for total and labelled N analysis by the methods described by Bremner[3,4]. The labelled N analysis were made using a mass-spectrometer (Consolidated Electrodynamic Corporation, USA, model 21–620–A). The small contributions of the immobilized N left over in the soil from the previous year was not taken into consideration in the calculation of fertilizer N utilization by the second rice crop.

During 1977, measurements of gaseous losses were made by providing a special assembly with the lysimeters as shown in Fig. 1. Leaching losses from the bottom hole of the lysimeters were also estimated. For collecting gases the lysimeters were enclosed with an acrylic cover, having provision of 4 glass tubes (2.5 cm diameter) for the rice plant to grow in the open atmosphere. The gases evolved in the soil surface were made to flow from the enclosed system, through a set of gas bubblers towards a glass carbuoy filled with water, by aspiration. The rate of flow of gases towards the carbuoy was adjusted so as to collect 1 litre of gas per 2 hours by displacement of an equal amount of water from the carbuoy daily in the morning and in the evening for 70 days. The gas bubbler assembly had a provision for absorption of NH_3 in the H_2SO_4; carbon dioxide and oxides of N into the KOH and oxygen into the pyrogallol. Thus only N_2 gas was collected in the carbuoy. The gas collected in the carbuoy was freeze-dried by passing through a moisture-trap containing liquid nitrogen and samples were collected in glass ampoules. The ^{15}N-content in the gas ampoules was determined by using mass spectrometer and the results were calculated by the method described by Hauck *et al.*[11]. Ammonia and oxides of N absorbed in H_2SO_4 and KOH respectively were also estimated.

Availability of residual fertilizer nitrogen

The availability of residual labelled fertilizer N applied to the rice crop, was tested on the wheat crop in 1976–77 and wheat and rice in 1977–78. A basal dose of 120, 26 and 56 kg/ha of N, P and K respectively was applied. Five plants of wheat variety S-308 and four seedlings of rice variety PR 103 were grown to maturity and the grain and straw yields were recorded and samples collected for total N and labelled N determination.

Results and discussion

Yield, N content and uptake of total N

Table 1 shows that there was considerable response of rice grain and straw to N application irrespective of time of application in both years. The rice yield was slightly less during 1976 and considerably more during 1977 with split application than single N application. The content and uptake of N for the rice grain and straw (Table 1 b, c) was considerably more with split application of N. Significant responses of rice to N application were obtained by Meelu *et al.*[18] in Punjab and elsewhere in the country[13,19,23]. Better performance of split

Table 1. Effect of different treatments on rice yield N-content and N uptake per lysimeter

Sr. No.	Treatment	Rice grain			Rice straw			Grain + straw		
		1976	1977	Mean	1976	1977	Mean	1976	1977	Mean
a)	*Yield (g)*									
1.	Check	38.0	18.3	28.4	23.7	26.7	25.2	–	–	–
2.	N-single application	81.0	46.2	63.6	61.0	64.1	62.5	–	–	–
3.	N 3 split application.	78.8	53.0	65.9	55.5	72.4	63.9	–	–	–
b)	*N-content (%)*									
1.	Check	0.95	1.17	1.06	0.49	0.72	0.61	–	–	–
2.	N-single application	0.85	1.05	0.95	0.43	0.60	0.52	–	–	–
3.	N 3 split application	1.02	1.20	1.11	0.48	0.68	0.58	–	–	–
c)	*N-uptake (g)*									
1.	Check	0.361	0.218	0.290	0.116	0.192	0.154	0.477	0.410	0.444
2.	N-single application	0.770	0.485	0.628	0.308	0.386	0.347	1.078	0.871	0.975
3.	N 3 split application	0.804	0.726	0.765	0.266	0.493	0.380	1.070	1.019	1.045

application than single N application may be what should be expected because the N applied at growth stages synchronizing with the demand of the crop may be more efficient than a single application at transplanting. However, a lower yield of rice in 1976 with split application may be ascribed to the late transplanting of the crop in that year. Allen and Terman[1] also found that N application at later stage of growth of rice was not effective for yield response but increased the N content of the rice grain and straw.

Table 2. Utilization of fertilizer N by rice

Sr. No.	Treatment	Fertilizer N utilization (percent)								
		Rice grain			Rice straw			Grain + straw		
		1976	1977	Mean	1976	1977	Mean	1976	1977	Mean
1.	N-single application	13.4	19.6	16.5	4.8	5.5	5.1	18.2	25.1	21.6
2.	N-3 split application	24.6	33.7	29.2	6.5	19.3	12.9	31.1	53.0	42.0

Utilization of fertilizer ^{15}N by rice

The utilization of fertilizer N by rice is given in Table 2. The data show that split application of N gave better fertilizer use efficiency than single N application. The mean fertilizer use efficiency was 42.0 and 21.6 per cent for the split and single application, respectively; 29.2 and 16.5 per cent of the fertilizer N was taken up by grain and 12.9 and 5.1 per cent by the straw from split and single N application treatments, respectively.

It may be observed that N application increased grain and straw production 2–3 fold, but the utilization of fertilizer N was low (21.6 to 42.0 per cent). The low utilization of N may be ascribed to the immobilization, leaching and gaseous losses of applied N under rice culture. The studies on flooded rice using fertilizer ^{15}N in the USA[15,24] and Philippines[9,36] also reported that utilization of fertilizer N varied from 12 to 50 per cent.

More utilization of fertilizer N with a split than a single application showed a higher efficiency of N from the former treatment. In the later case, fertilizer N was subject to chemical and biological conversions for a longer period of time and thereby decreased the fertilizer use efficiency by the rice crop[9,22,27].

Comparison of fertilizer N utilization in rice by difference method and ^{15}N technique

The utilization of N determined by ^{15}N technique was compared with utilization obtained by difference method[22]. Nitrogen uptake by difference method was calculated as the difference between total N uptake from the fertilized and unfertilized soil (check). Table 3 shows that difference method resulted in higher N utilization compared with the isotope dilution technique. Similar results were reported by Zamyatina[39], Hauck[10] and Reddy and Patrick[28]. The higher N utilization obtained by difference method may be ascribed to the greater utilization of native soil N by the fertilized crop as compared with the unfertilized crop, a phenomenon commonly known as priming effect. However, the wide gap in N utilization by two methods also call for refinement in experimental and analytical technique in ^{15}N studies.

Table 3. Fertilizer N utilization calculated by two different methods

Sr. No.	Treatment	Fertilizer N utilization (%)	
		Difference method	$^{15-}$N-technique
1.	N-single application	41.7	21.6
2.	N-3 split application	47.3	42.0

Gaseous losses

An estimate of the fertilizer N lost in the form of gases was obtained by making appropriate provision for collection of gases and measurement of ^{15}N as discussed below.

Ammonia volatilization

Table 4 shows that only small amounts of fertilizer N were lost by ammonia volatilization. This may be attributed to quick adsorption of NH_4^+ ions on the colloidal complex of soil after conversion from urea. However, the technique used may have underestimated the losses. Various workers[20,33,35] have reported volatilization losses ranging from 0.25 to 20 per cent using the continuous air flow system for collection of ammonia; this technique might overestimate the volatilization losses due to fast swirling of the flood water. A better technique to measure volatilization losses in natural rice ecosystem under field conditions need to be developed.

Denitrification

Table 4 shows that denitrification loss as N_2 gas were 4.8 to 7.2 per cent of the applied fertilizer N with split and single application, respectively. The loss was less with split application of fertilizer than with single application. The N lost as N_2O or NO gases was almost nil (0.0001 per cent).

Most of the reports on gaseous losses are obtained indirectly as unaccounted for N and are reported from 20 to 50 per cent of the applied fertilizer N[15,16,22,31].

Fertilizer N retained in the soil

After the harvest of each crop soil samples from different depths were taken to see the ^{15}N distribution in the profile. Table 5 and Fig. 2 show that after the harvest of the rice crop in 1976, 40.7 to 41.1 per cent of the fertilizer N was retained in the soil. The vertical distribution indicated the highest concentration of fertilizer N (38.3 to 39.5 per cent) in the surface (0–30 cm) soil. The content sharply decreased (1.8 to 2.4 per cent) in lower (30–150 cm) soil layers. The soil

Table 4. Effect of N application method on gaseous losses of fertilizer N

Sr. No.	Treatment	NH_3-volatilization (%)	Denitrification (%)
1.	N-single application	0.02	7.2
2.	N-3 split application	0.01	4.8

Table 5. Distribution of fertilizer N in the soil profile after the harvest of crops

Sr. No.	Treatment	Depth (cm)	Labelled fertilizer N(mg/lysimeter) in the soil after				
			Rice 1976	Wheat 1976–77	Rice 1977	Wheat 1977–78	Rice 1978
1.	N-single application	0– 15	371	257	661	560	473
		15– 30	116	99	196	129	157
		30– 60	18	44	9	78	58
		60– 90	–	50	14	68	42
		90–120	13	20	16	–	33
		120–150	–	4	9	–	45
		Total	518(40.7)	474(37.3)	905	834	808
2.	N-split application	0– 15	457	226	623	347	320
		15– 30	46	93	76	142	188
		30– 60	14	63	31	155	96
		60– 90	–	34	24	26	39
		90–120	6	28	11	18	24
		120–150	–	20	19	3	25
		Total	523 (41.1)	464 (36.6)	784	731	692

Figures in parenthesis indicate percentage of applied fertilizer N.

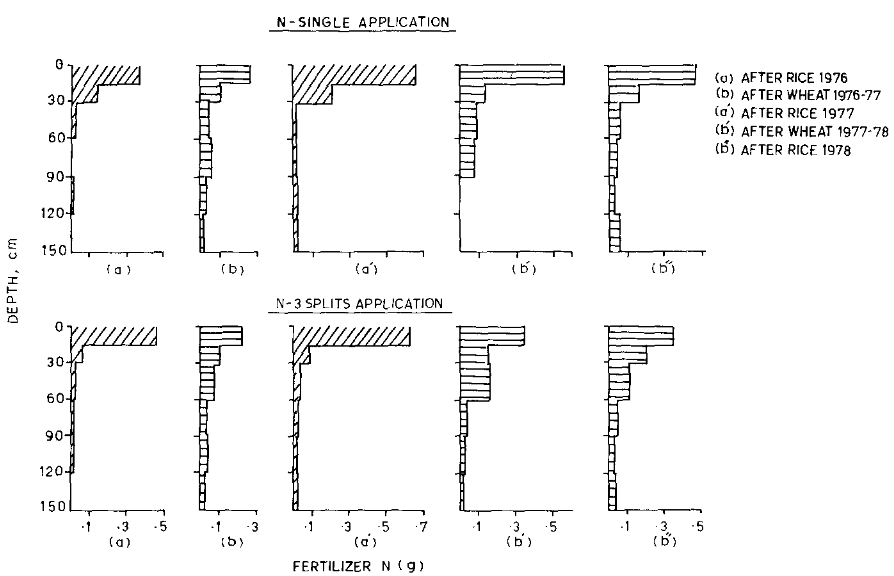

Fig. 2. Distribution of fertilizer nitrogen (^{15}N) in lysimeter soil profile.

analysis after the harvest of succeeding wheat crop (1976–77) showed that the ^{15}N content tended to decrease in the surface soil with simultaneous increase in the lower layers irrespective of treatments. The soil analysis after the rice crop in 1977 and the succeeding wheat and rice crops showed that the ^{15}N distribution in different soil layers followed the same pattern as observed during the previous year.

The results revealed that about 2/5th of applied fertilizer N was retained in the soil after the harvest of rice. The retention of fertilizer N in the soil may be attributed to its conversion to organic forms, assimilation by the soil micro-organism, sorption on the collidal complex of soil and fixation by the clays. Manguiat and Broadbent[15] Patrick and Reddy[24] also found about 1/4th to 1/3rd of the applied fertilizer N in the soil at the harvest of rice.

The decrease in fertilizer N in surface soil and simultaneous enrichment in the sub-surface after wheat may be attributed to the uptake of fertilizer N by the crop and its movement by diffusion or mass flow from the surface to the sub-soil layers. Further wheat is an upland crop and the soil environment provide better conditions for the transformation of organic N to the nitrate form, which in turn may move down into the lower layers of soil with successive irrigations. Based on thermodynamic equations Ponnamperuma[25], reported that there was a tremendous driving force for the oxidation of N-compounds to the nitrate form in the aerobic soil media. Daftardar[7] also reported more downward movement of fertilizer N during the wheat crop growth as compared to rice.

Balance sheet of applied ^{15}N-labelled urea

The balance sheet of applied ^{15}N (Table 6) shows that the total recovery of

Table 6. Balance sheet of ^{15}N-labelled urea in rice culture

Treatment	Percent of fertilizer nitrogen						
	Plant uptake	Retained in soil	NH_3-volatilization	Denitrification		Total recovery	Unaccounted
				N-oxides	N_2gas		
I. 1976							
N-single application	18.1	40.7	nd.	nd.	nd.	58.8	41.2
N split application	31.1	41.1	nd.	nd.	nd.	72.2	27.8
II. 1977							
N-single application	25.1	33.9	.02	traces	7.2	66.2	33.8
N-split application	53.0	25.2	.01	traces	4.8	83.0	17.0

Table 7. Utilization of residual fertilizer N by succeeding crops

Sr. No.	Treatment	Utilization of fertilizer N(% of amount applied)								
		Grain			Straw			Grain + straw		
		Wheat 1976–77	Wheat 1977–78	Rice 1978	Wheat 1976–77	Wheat 1977–78	Rice 1978	Wheat 1976–77	Wheat 1977–78	Rice 1978
1.	N-single application	2.4	2.1	1.5	0.4	0.4	0.6	2.8	2.5	2.1
2.	N split application	2.6	3.2	1.7	0.6	0.2	0.6	3.2	3.4	2.3

fertilizer N from the soil-plant system ranged from 58.8 to 72.2 per cent in 1976 and 66.2 to 83.0 per cent in 1977. The unaccounted for fraction ranged from 27.8 to 41.2 per cent, and 17.0 to 33.8 per cent. The nitrogen balance sheet data of Broeshart[6], Patrick and Reddy[24] also showed 7 to 62 per cent deficits of the applied ^{15}N. In these studies the unaccounted for nitrogen was generally attributed to gaseous losses. The results of this study and those reported elsewhere indicate that considerable part of the applied nitrogen remained unaccounted for by the present techniques. Therefore, more research need to be done to determine the fate of unaccounted for nitrogen in the balance sheet.

Residual effect of fertilizer nitrogen applied to rice on the succeeding crops

Table 7 shows that during both years the wheat crop utilized 2.5 to 3.4 per cent of the fertilizer N applied to rice. Another 2.2 to 2.3 per cent N was used by the rice crop grown in succession. The low utilization of fertilizer N immobilized in the soil may be due to its conversion into organic forms[26], fixation on the biomolecules[12] and the non-biological interaction with the inorganic matrix of the soil. Bartholomew[2] observed that only 1 to 5 per cent of the fertilizer N immobilized in the soil was released for crop use each year. Daftardar[7] recovered 1.7 to 3.2 per cent of residual fertilizer N in the rice-wheat rotation. Oza and Subbiah[21] obtained residual N recovery of 0.1 to 2.3 and 0.2 to 0.3 per cent in the first and second crop respectively. Manguiat and Broadbent[15], Reddy and Patrick[28] in the USA; Yoshida and Padre[37] in the Philippines and Yoshino and Dei[38] in Japan reported residual ^{15}N recovery in the range of 1 to 5.8 per cent.

It may be concluded from this discussion that about 3 to 5 kg N/ha could be discounted from the N application to the succeeding crop due to the residual N from the previous crop. This is small but may not be insignificant on a long term basis. However, there is need for long term studies on this aspect to investigate year to year turnover of residual N from the soil.

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References

1 Allen S E and Terman C L 1978 Yield and protein content of rice as affected by rate, source, method and time of applied N. Agron. J. 70, 238–242.

2 Bartholomew W V 1965 Mineralization and immobilization in the decomposition of plant and animal residues. *In* Soil Nitrogen pp 285–306. Eds. W V Bartholomew and F E Clark. Am. Soc. Agron. Madison, Wisconsin.

3 Bremner J M 1965 Total nitrogen. *In* Methods of Soil Analysis Part 2. pp 1149–1176. Eds. C A Black *et al.* Am. Soc. Agron. Madison, Wisconsin.

4 Bremner J M 1965 Isotope ratio analysis of nitrogen in ^{15}N tracer investigation. *In* Method of Soil Analysis Part 2. pp 1256–1286. Eds. C A Black *et al.* Am. Soc. Agron. Madison, Wisconsin.

5 Broadbent F E and Nakashima T N 1970 Nitrogen immobilization in flooded soils. Soil Sci. Soc. Am. Proc. 54, 218–221.

6 Boreshart H 1971 The rate of nitrogen fertilizer in flooded rice soils. *In* Nitrogen-15 in Soil Plant Studies Vienna, Austria, International Atomic Agency. pp. 47–54.

7 Deftardar S Y 1973 Urea and ammonium nitrate fertilizers for low land rice. Studies with 15-N tagged materials on nitrogen transformation, losses and utilization. Ph.D. Thesis, IARI, New Delhi.

8 Datta N P, Banerjee N K and Prasada Rao D M V 1971 A new technique for study of nitrogen balance sheet and an evaluation of nitrophosphate using 15-N under submerged conditions of growing paddy. Proc. International. Symp. Soil Fert Eval., New Delhi. 1, 631–638.

9 De Datta S K, Magnaya C P and Moomaw J C 1968 Efficiency of fertilizer nitrogen (15-N labelled) for flooded rice. Trans. 9th Intern. Congr. Soil Sci. 4, 67–76.

10 Hauck R D 1971 Quantitative estimates of nitrogen-cycle processes. Concept and review. *In* Nitrogen-15 in Soil-Plant Studies. Vienna, Austria. International Atomic Energy Agency, pp 65–80.

11 Hauck R D, Melstead S W and Yankwich P E 1958 Use of N-isotope distribution in nitrogen gas in the study of denitrication, Soil Sci. 86, 287–291.

12 Kai H and Wada K 1978 Chemical and biological immobilization of nitrogen in paddy soil. *In* Nitrogen and Rice. Manila, Philippines. Intern. Rice Res Inst.

13 Khind C S and Datta N P 1975 Effect of method and timing of nitrogen application on yield and fertilizer nitrogen utilization by low land rice. J. Indian. Soc. Soil Sci. 23, 442–446.

14 Koshino, M 1973 Incoming and outgoing of fertilizer nutrients in crops lands. I. Proc. of the Intern. Congr. on the Human Environment, HESC Organizing Committee Science Council of Japan, pp 206–214.

15 Manguiat I J and Broadbent F E 1977 Recoveries of tagged N (15-N labelled) under some management practices for low land rice. Philipp. Agric. 60, 367–377.

16 Maguiat U J and Yoshida T 1973 Nitrogen transformation of ammonium sulphate and alanine in submerged Maahas clay. Soil. Sci. Pl. Nutr. 19, 95–102.

17 McGill W B and Paul E A 1976 Fractionation of soil and ^{15}N nitrogen to separate the organic and clay interactions of immobilized N. Can. J. Soil Sci. 56, 203–212.

18 Meelu O P, Gill H S and Maskina M S 1980 Substitution of nitrogen through organic manures. Prog. Fmg. 16, 13.

19 Meelu O P 1980 Personal Communication.

20 Mikkelsen D S, De Datta S K and Obcemea W N 1978 Ammonia volatilization losses from flooded rice soils. Soil Sci. Soc. Am. J. 42, 725–730.

21 Oza A M and Subbiah B V 1980 Utilization of fertilizer nitrogen and its distribution in the soil profile under a multiple cropping system. J. Indian Soc. Soil Sci. 28, 85–90.

22 Patnaik S N 1965 Tracer studies on the transformation of applied nitrogen in submerged rice soils. Proc. Indian Acad. Sci. Sect. B 61, 25–30.

23 Patnaik S M, Rao V and Nanda B B 1968 Some considerations of nitrogen uptake by high yielding rice varieties. Intern. Rice Comm. News. Lett. 17, 26–37.

24 Patrick W H Jr and Reddy K R 1976 Fate of nitrogen in a flooded rice oil. Soil Sci. Soc. Am. J. 40, 678–681.

25 Ponnamperuma F N 1972 The chemistry of submerged soils. Adv. Agron. 24, 29–93.

26 Porter L K, Viets F G Jr and Hutchinson G L 1972 Air containing nitrogen-15 ammonia; foliar absorption by corn seedlings. Science 175, 759–761.

27 Prasad R and DeDatta S K 1978 Increasing fertilizer efficiency in wetland rice. *In* Nitrogen and Rice Manila, Philippines, Intern. Rice Res. Inst.

28 Reddy K R and Patrick W H Jr 1976 Yield and nitrogen utilization by rice as affected by method and time of application of nitrogen. Agron. J. 68, 965–969.

29 Reddy K R and Patrick W H Jr 1978 Residual fertilizer N in a flooded rice soil. Soil Sci. Soc. Am. J. 42, 316–318.

30 Subbiah B V and Asija G L 1956 A rapid procedure for the estimation of available nitrogen in soils. Curr. Sci. 25, 259–260.

31 Tusneem M S and Patrick W H Jr 1971 Nitrogen transformation in waterlogged soils. Louisiana State Univ. Bull. 657 USA.

32 Upadhaya G S, Datta N P and Deb D L 1974 Note on the effect of selected drainage practices on yield of rice and the efficiency of nitrogen use. Indian J. Agric. Sci. 43, 888–889.

33 Ventura W B and Yoshida T 1977 Ammonia volatilization from a flooded tropical soil. Plant and Soil 46, 521–531.

34 Vlek P L G and Craswell E T 1979 Effect of nitrogen source and management on ammonia volatilization losses from flooded rice soil systems. Soil Sci. Soc. Am. J. 43, 352–358.

35 Vlek P L G and Stumpe J M 1978 Effect of solution chemistry and environmental conditions on ammonia volatilization losses from aqueous systems. Soil Sci. Soc. Am. J. 42, 416–421.

36 Yoshida T and Padre Jr B C 1975 Effect of organic matter application and water regimes on the transformation of fertilizer N in a Phillipines soil. Soil Sci. Pl. Nutr. 21, 281–292.

37 Yoshida T and Padre Jr B C 1977 Transformation of soil and fertilizer nitrogen in paddy soil and their availability to rice plants. Plant and Soil 47, 113–123.

38 Yoshino T and Dei Y 1977 Prediction of nitrogen release in paddy soils by means of the concept of effective temperature. J. Cen. Agric. Expt. Stn. Japan. 25, 1–62.

39 Zamyatina V B 1971 Nitrogen balance studies using ^{15}N-labelled fertilizers. *In* Nitrogen-15 in Soil Plant Studies, Vienna Austria. Intern. Atomic Energy Agency. pp. 33–46.