Biol Fertil Soils (2002) 35:27–34
DOI 10.1007/s00374-001-0436-2

ORIGINAL PAPER

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Fate of nitrogen-15-labelled fertilizer applied to maize-millet cropping systems in the mid-hills of Nepal

Received: 4 December 2000 / Published online: 22 January 2002

Abstract Maize grown in the mid-hills of Nepal traditionally received inputs of manure. However, N fertilizer is increasingly applied either alone or in combination with manure. This study investigated the effect of these different nutrient sources applied at three rates (0, 45, 90 kg N ha^{-1}) on crop yields in a maize-millet rotation at two locations (Pakhribas and Dordor Gaun) in the mid-hills of Nepal and measured the recovery of ^{15}N-labelled urea applied as a top-dressing to maize at three rates (11.25, 22.5, 45 kg N ha^{-1}). Grain and straw yields of maize were greater following the application of fertilizer either alone or in combination with manure, rather than manure alone. Millet yields were unaffected by the rate or form of N inputs to maize. Little (<25%) of the applied fertilizer was recovered in the maize crop, with only a further 3% recovered by the subsequent millet crop. On average, 58% of the applied fertilizer was recovered in the 0- to 60-cm soil layer at maize harvest, mainly in non-mineral N forms. Transformations and movement of applied fertilizer N were shown to be rapid, occurring within 7 days of application. Approximately one-third of the applied fertilizer was unaccounted for in the crop-soil system at maize harvest. It was concluded that fertilizer was rapidly immobilized and that its subsequent rate of turnover was low so that an application of fertilizer to one crop made no substantial contribution to the nutrition of the next.

Keywords Maize · Millet · Nitrogen fertilizer recovery

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Introduction

Maize-based cropping systems cover more than 90% of the estimated 850,000 ha of rainfed terraces (bari-land) in the mid-hills of Nepal (LRMP 1986). Depending on altitude and location, maize (*Zea mays* L.) is grown in rotation with mustard, potato, rice or legume crops but most often it is grown in relay or sequential rotations with finger millet (*Eleusine coracana* L.). Grain yields of both maize and millet are stagnant, averaging 1.6 t ha^{-1} and 1.1 t ha^{-1}, respectively, between 1969/1970 and 1992/1993 (Thapa and Rosegrant 1995). While cultivating a larger area has increased overall production in Nepal, this is not a viable option in the mid-hills where cultivable land area is limited.

Traditionally, the major source of nutrients for crops in the mid-hills of Nepal has been farmyard manure (FYM) and compost. However, there is increasing concern among hill farmers that FYM sources are insufficient to match the requirements for household crop production (Turton et al. 1995). The decline in availability of FYM has occurred at the same time as there has been an increase in the availability of fertilizers in those areas served by a developing network of roads and markets. Elsewhere, several workers have demonstrated that sustainable crop production is only achievable at the levels of production required, if appropriate amounts of both inorganic fertilizers and organic materials are applied in combination (Greenland et al. 1998; Powlson and Johnston 1994). The availability of nutrients in fertilizer, manure and fertilizer plus manure differs and this may have implications not only for the crop to which they are applied but also for the subsequent crop.

The recovery of N by crops may be determined using both unlabelled and labelled N fertilizer (Harmsen and Moraghan 1988) but the measurement of the recovery of fertilizer N in the soil, and the subsequent calculation of N losses from the crop-soil system, can only be made using ^{15}N-labelled fertilizer (Powlson et al. 1992). Recovery of N fertilizer in the crop-soil system is affected by N losses, which may be large during the monsoon rains that occur in Nepal.

This paper reports the results of experiments in which ^{15}N-labelled fertilizer was applied at different rates either alone or in combination with manure, to maize grown in rotation with millet at two locations in the mid-hills of Nepal. The aims were to quantify: (1) the yield of both maize and millet in a single rotation in response to the application of fertilizer, manure or manure plus fertilizer to maize; and (2) the balance of N fertilizer at both maize and millet harvest, by determining the amount of fertilizer N taken up by the plant, the recovery of N fertilizer in soil and consequently the amount of N fertilizer lost from the system.

Materials and methods

Long-term recovery of ^{15}N-labelled fertilizer

Maize-millet rotations were grown at two locations in the mid-hills of Nepal, one at Pakhribas (87°17′E, 27°17′N), Dhankuta District, Eastern Region, where millet was transplanted before maize was harvested (i.e. grown in relay) and the other at Dordor Gaun (84°20′E, 28°10′N) in Bhanu district, Western Region where millet was transplanted after maize was harvested (i.e. grown sequentially). Selected soil properties of Pakhribas (sandy loam) and Dordor Gaun (silt loam) are reported in Table 1. Average monthly maximum and minimum temperatures were greater at Dordor Gaun than at Pakhribas (Fig. 1). Temperatures were generally greatest in May and June and lowest in January. In 1998, 1,340 mm rain fell at Pakhribas and 1,683 mm at Dordor Gaun with the heaviest rain in August (Fig. 1).

Maize (*Zea mays* L. cv. Manakamana-1) was sown on 16 April 1998 at Pakhribas and on 26 April 1998 at Dordor Gaun. The plots measured 6 m×3.75 m at Pakhribas and 6 m×4 m at Dordor Gaun, but at both locations the maize rows were 75 cm apart with 25 cm between plants in the row. Seven treatments, based on the form and rate of N supply (Table 2) were replicated 4 times in a randomized complete block design. P was added as diammonium phosphate and K was added as muriate of potash as basal dressings at rates that were proportional to N rates to ensure an approximately balanced supply of nutrients (Table 2). The P and K contents of the manure were not measured, and so applica-

Table 1 Characteristics of the 0- to 25-cm layer of soils at Pakhribas and Dordor Gaun in Nepal

Characteristic	Pakhribas	Dordor Gaun
Total N (%)	0.080	0.078
Available P (mg kg^{-1})	20.84	31.39
Organic C (%)	1.32	0.82
pH	6.0	5.4
Sand (%)	62	30
Silt (%)	26	41
Clay (%)	12	29

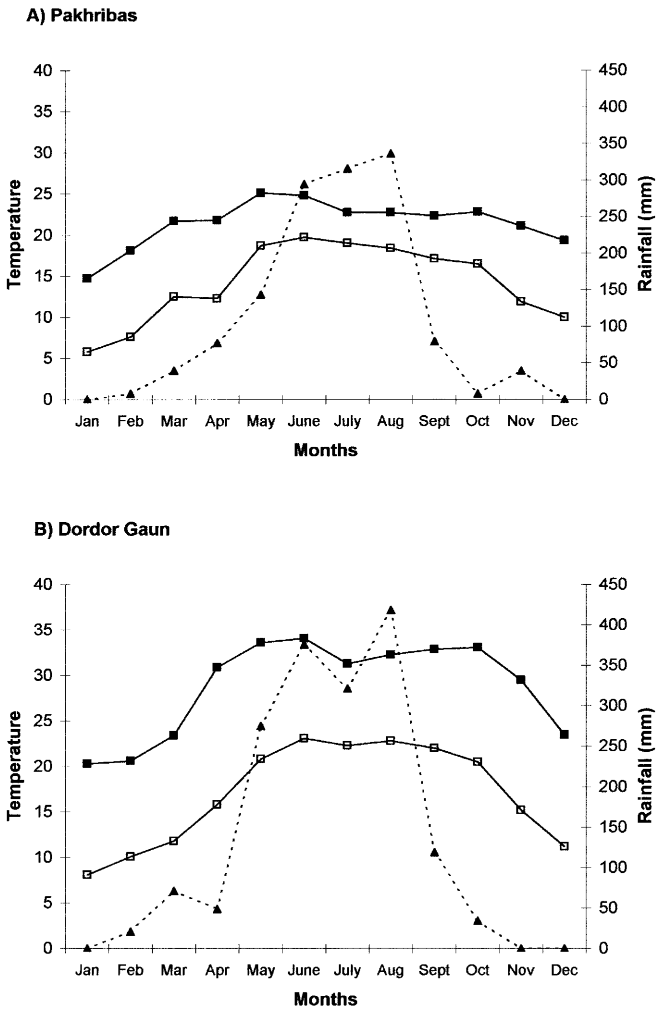

Fig. 1 Monthly average maximum (■) and minimum (□) temperature (°C) and monthly rainfall totals (mm; ▲) for **A** Pakhribas, and **B** Dordor Gaun in 1998

Table 2 Form, timing and rate of N, P and K applications in each of the seven experimental treatments

Treatment	Form and timing of application					
	Basal manure (kg N ha^{-1})	Basal N fertilizer (kg N ha^{-1})	Top-dresse fertilizer (kg N ha^{-1})	Total N application (kg N ha^{-1})	Basal P fertilizer (kg P ha^{-1})	Basal K fertilizer (kg K ha^{-1})
1	0	0	0	0	0	0
2	0	45	45	90	30	30
3	90	0	0	90	0	0
4	45	22.5	22.5	90	15	15
5	0	22.5	22.5	45	15	15
6	45	0	0	45	0	0
7	22.5	11.25	11.25	45	7.5	7.5

N.B. Unquantified additions of P and K will have been added basally to those treatments receiving manure tion rates of P and K in manure were not known. The composition of manure at Pakhribas was 0.7%N on a fresh weight basis and 46.4% dry matter, and that at Dordor Gaun was 2.1% N and 27.7% dry matter.

Maize was top-dressed with urea-N on 8 June 1998 at Dordor Gaun and on 16 June 1998 at Pakhribas. A 4 m×1.5 m microplot was established in the centre of each plot of treatments 2, 4, 5, and 7, and ^{15}N-labelled urea (10.3616 atom%) applied at the appropriate rate in 6 l of solution using a watering can. The remainder of the plot was top-dressed with unlabelled urea at the same time. Maize plots were weeded at Dordor Gaun prior to top-dressing and on 6 August 1998 and the dry weight of the weeds from a known area was determined.

Maize was harvested on 18 and 19 August 1998 at Dordor Gaun and on 6 and 7 September 1998 at Pakhribas. At both locations the 4-m-long microplot was divided into four 1-m-wide strips each 1.5 m long. Four plants were harvested at ground level from the centre of a single strip from each microplot and for treatments 1, 3 and 6, four plants were taken at random. The four plants from each plot were weighed and divided into grains, rachis and stover. Subsamples of each were taken, weighed and dried in an oven at 80°C to constant weight. After removing a single plant from the borders of each plot, the remainder of the plot was harvested at ground level. The total weight of biomass was measured and the grains separated from the cobs. The total fresh weight of grains was measured and corrected for moisture content.

The plant material taken for the analysis of yield components from treatments 1, 2, 4, 5 and 7 was ground to pass a 2-mm sieve and the N content and ^{15}N enrichment determined by total combustion on a Roboprep C and N analyser (Europa Scientific Crewe) linked to a VG602 mass spectrometer.

Soil samples were taken from the microplots after maize harvest at both locations. A 30 cm×30-cm grid was placed in the centre of the area from which the maize was harvested. Soil was dug to a depth of 20 cm, sieved through a ca. 10-mm mesh, mixed thoroughly and subsampled. Two further soil samples were also taken from the 20- to 40-cm and 40- to 60-cm soil layers in the base of this hole using a 6-cm-diameter auger at Pakhribas and a 4-cm-diameter auger at Dordor Gaun. The soil samples were air dried, ground and analysed for total N and ^{15}N enrichment on a Roboprep C and N analyser (Europa Scientific Crewe) linked to a VG602 mass spectrometer.

Finger millet (*Eleusine coracana* L. cv Okhale-1) was transplanted from a nursery bed in rows 10 cm apart with 10 cm between plants on 18 July 1998 at Pakhribas and on 21 August 1998 at Dordor Gaun. It was harvested on 26 November 1998 at Pakhribas and on 7 December 1998 at Dordor Gaun. At maturity, plants in treatments 1, 2, 4, 5 and 7 were cut at ground level from an area 50 cm×70 cm within a previously unsampled part of the microplot. The plants were separated into straw and panicle, which was, in turn, separated into grain and chaff. The fresh and dry weights of all components were determined. The remainder of the plot was harvested at ground level and the weight of straw and grain determined. At both locations, soil samples were taken from within the 50 cm×70-cm area from which the millet was harvested, using a method identical to that used following the maize harvest.

The N content and ^{15}N enrichment of millet and weed samples and soil samples were measured in a manner identical to that for the maize samples. The recovery of applied ^{15}N fertilizer in plants and soil were calculated according to the methods described by Hauck and Bremner (1976) using 0.3663 atom% as the background enrichment of fertilizer and 0.3772 atom% as the background enrichment of plant and soil samples. Bulk densities of the 0- to 20-cm, 20- to 40-cm and 40- to 60-cm soil layers at Pakhribas were 1.43±0.038, 1.57±0.032 and 1.52±0.024 Mg m^{-3}, respectively. The bulk density at Dordor Gaun was assumed to be a uniform 1.4 Mg m^{-3}.

Data were analysed by ANOVA using Genstat 5 (version 3.2). Data from the two locations could not be combined because the variances from the two locations were not homogeneous.

Short-term recovery of ^{15}N-labelled fertilizer

Twenty plastic tubes (52 mm internal diameter) were inserted so that the top edge was flush with the surface of the soil in a fallow area of the Pakhribas site. Four of the cores were 10 cm long and 16 were 25 cm long. ^{15}N-labelled urea (10.3616 atom%) was applied on 17 June 1998 at a rate of 45 kg N ha^{-1} (i.e. 23.9 mg N per core) in 2 ml of solution to the surface of each core. The four shorter (10 cm long) cores were excavated after 30 min (day 0) and four of the remaining 16 cores were excavated on each of days 1, 2, 4 and 7 after application of the ^{15}N-labelled fertilizer.

After excavation the cores were divided into 0- to 5-cm and 5- to 10-cm (day 0) or 0- to 5-cm, 5- to 15-cm and 15- to 25-cm layers (days 1, 2, 4 and 7) and then weighed. A subsample of soil was taken for the determination of water content and another sample of 70 g was placed in 300 ml of 1 M KCl containing 5 ppm phenylmercuric acid, a urease inhibitor (Mulvaney and Bremner 1979) in an Erlenmeyer flask and shaken for 1 h at 150 r.p.m. The soil solutions were filtered through GF/A filter papers. The solids remaining on the filter paper were rinsed with distilled deionized water, dried at 105°C for 48 h, weighed and ground in a TEMA mill. All N in these solids was assumed to be organic.

NH_4^+ and NO_3^- concentrations in the extracted solutions were determined on a flow injection analyser (Tecator FIAstar 5010). ^{15}N enrichment of these mineral N fractions was determined on a VG622 mass spectrometer using a modified version of the diffusion method (Brookes et al. 1989). Urea in the extract was determined colorimetrically using a modified diacetyl monoxime method (Mulvaney and Bremner 1979). The ^{15}N enrichment of the urea in the extract was assumed to be that of the fertilizer (10.3616 atom%). N content and ^{15}N enrichment of the organic N pool were determined following total combustion on a Roboprep C and N analyser (Europa Scientific Crewe, UK) linked to a VG 622 mass spectrometer. Fertilizer recovery in each of the N pools (NH_4^+, NO_3^-, urea and organic N) was calculated as by Hauck and Bremner (1976).

Results

Biomass and grain yield

Grain and shoot biomass of maize were both greater at Pakhribas than at Dordor Gaun (Table 3). Additions of fertilizer either alone or in combination with manure increased significantly the grain ($P<0.001$) and straw ($P<0.05$) yields of maize given either no input or manure-only treatments (Table 3). On average, an addition of 45 kg N ha^{-1} increased the grain yield by 299 kg ha^{-1}, over the unfertilized plot. A further addition of 45 kg N ha^{-1} increased the grain yield by another 479 kg ha^{-1}. An input of 90 kg N ha^{-1} therefore increased maize yields by 778 kg ha^{-1} on average over the unfertilized plot.

In contrast to maize, the total shoot biomass of millet was similar at both locations (Table 3), although grain yields were larger, on average, at Pakhribas (1717 kg ha^{-1}) than at Dordor Gaun (1336 kg ha^{-1}). Generally, there was no significant effect of N additions in any form on yield (Table 3), although there was a trend for millet crops grown on previously manured plots to yield more than those that had previously received only fertilizer, or nothing.

Table 3 Effects of treatments on average grain and shoot biomass of maize and millet grown at Pakhribas and Dordor Gaun in 1998. A SE of the difference of the means (*SED*) is shown

Location	Treatment	Maize		Millet	
		Grain	Shoot biomass	Grain	Shoot biomass
		(kg ha^{-1})			
Pakhribas	1	1,369	4,301	1,621	3,883
	2	2,335	6,496	1,735	3,736
	3	1,861	5,530	1,847	4,609
	4	2,185	6,599	1,779	4,078
	5	1,844	5,992	1,728	3,911
	6	1,323	4,311	2,046	4,765
	7	1,837	5,304	1,724	3,926
	SED	327.0	776.5	272.9	680.2
Dordor Gaun	1	661	2,043	1,281	3,866
	2	1,853	3,853	1,026	3,479
	3	1,129	2,731	1,305	3,965
	4	1,397	3,094	1,617	4,859
	5	1,029	2,709	1,416	4,113
	6	898	2,440	1,455	4,371
	7	954	2,260	1,339	4,302
	SED	184.2	345.9	115.2	259.7

Table 4 Effects of treatments on the uptake of labelled and unlabelled N by maize and retention of labelled N in soil at Pakhribas and Dordor Gaun in 1998 following a top-dressed application of ^{15}N-labelled urea to maize. *Values in parentheses* are percentage recoveries in the different fractions. An SED is shown

Location	Treatment	N in crop at harvest (grain and stover)			Labelled N remaining in the soil after harvest				Labelled N unaccounted for
		(kg N ha^{-1})							
		Labelled	Unlabelled	Total	0–20 cm	20–40 cm	40–60 cm	Total	
Pakhribas	1	0	26.1	26.1	–	–	–	–	
	2	6.6 (14.7)	39.6	46.2	8.7 (19.3)	3.5 (7.8)	5.1 (11.3)	17.3 (38.4)	21.1 (46.8)
	4	3.7 (16.4)	38.2	41.9	1.0 (4.4)	4.9 (21.8)	4.9 (21.8)	10.8 (48.0)	8.0 (35.6)
	5	2.8 (12.5)	32.2	35.0	6.8 (30.1)	3.0 (13.2)	1.8 (8.0)	11.6 (51.3)	8.1 (36.2)
	7	1.4 (12.4)	30.2	31.7	2.1 (18.7)	3.9 (34.7)	1.8 (16.0)	7.8 (69.3)	2.1 (18.2)
	SED	0.60	5.59	6.01	2.66	2.48	3.00		
Dordor Gaun	1	0.3	13.2	13.5	–	–	–	–	
	2	9.6 (21.4)	21.8	31.4	4.1 (9.0)	3.6 (8.1)	2.6 (5.8)	10.3 (22.9)	25.1 (55.7)
	4	4.3 (19.1)	20.6	24.9	5.3 (23.6)	7.3 (32.4)	2.6 (11.6)	14.6 (64.9)	3.6 (16.0)
	5	4.2 (18.4)	19.0	23.2	6.0 (26.8)	3.6 (16.0)	5.5 (24.5)	15.1 (67.1)	3.2 (14.3)
	7	2.3 (20.4)	13.7	16.0	4.4 (39.1)	3.4 (30.2)	3.2 (28.4)	11.0 (97.8)	0 (0)
	SED	1.25	4.29	5.05	1.11	2.51	1.77		

Crop N

The N content of maize was significantly greater at Pakhribas than Dordor Gaun and increased with the addition of N to maize, irrespective of whether the N was applied as fertilizer alone, or in combination with manure (Table 4). For millet, the N content was also significantly greater at Pakhribas than at Dordor Gaun but there was no significant effect of any of the previous additions of N (Table 5).

Although crop recovery of fertilizer N was low (<10 kg N ha^{-1}) and decreased as the amount of fertilizer N applied decreased, the amount of fertilizer N recovered in maize was significantly greater at Dordor Gaun than at Pakhribas (Table 4). Overall, the percentage recovery of ^{15}N-labelled fertilizer was low (ranging from 12% to 21%).

Approximately 2 months after top-dressing maize with ^{15}N-urea, weeds at Dordor Gaun contained on average <2% of applied fertilizer (i.e. <0.5 kg N ha^{-1}).

Recovery of fertilizer N by millet crops was very low (<1 kg N ha^{-1}) at both locations but was slightly greater in treatments previously given fertilizer only than in treatments which had received fertilizer plus manure (Table 5). Recovery was also greater where inputs of fertilizer N were higher. The percentage recovery of N in millet was <3%, irrespective of rate of application, or whether it was applied in combination with manure or alone.

Uptake of soil N by both maize and millet was significantly greater at Pakhribas than at Dordor Gaun (Tables 4, 5). More soil N was taken up by maize receiving an input of fertilizer or fertilizer plus manure than

Table 5 Effects of treatments on the uptake of labelled and unlabelled N by millet and retention of labelled N in soil at Pakhribas and Dordor Gaun in 1998 following a top-dressed application of ^{15}N-labelled urea to a previous crop of maize. *Values in parentheses* are percentage recoveries in the different fractions. An SED is shown

Location	Treatment	N in crop at harvest (grain and straw)			Labelled N remaining in the soil after harvest				Labelled N unaccounted for
		(kg N ha^{-1})							
		Labelled	Unlabelled	Total	0–20 cm	20–40 cm	40–60 cm	Total	
Pakhribas	1	0.17	33.4	33.6	–	–	–	–	
	2	0.64 (1.4)	27.4	28.1	7.1 (15.7)	2.7 (5.9)	4.1 (9.1)	13.8 (30.7)	30.6 (67.9)
	4	0.36 (1.6)	33.2	33.6	7.4 (32.9)	3.0 (13.3)	5.5 (24.4)	15.9 (70.7)	6.2 (27.7)
	5	0.42 (1.9)	31.0	31.4	5.9 (26.2)	5.2 (23.0)	5.2 (23.0)	16.3 (72.2)	5.8 (25.7)
	7	0.23 (2.0)	34.4	34.7	4.7 (41.8)	3.2 (28.4)	3.6 (32.0)	11.4 (101.3)	0 (0)
	SED	0.11	6.27	6.36	2.20	1.19	1.71		
Dordor Gaun	1	0	25.5	25.5	–	–	–	–	
	2	0.55 (1.2)	26.1	26.7	9.2 (20.4)	6.6 (14.7)	5.7 (12.7)	21.5 (47.8)	23.0 (51.0)
	4	0.39 (1.7)	27.4	27.8	7.7 (34.2)	4.6 (20.4)	6.1 (27.1)	18.4 (81.7)	3.7 (16.5)
	5	0.4 (1.8)	24.1	24.5	6.8 (30.4)	5.2 (23.1)	4.8 (21.3)	16.8 (74.8)	5.3 (23.4)
	7	0.28 (2.5)	26.8	27.0	6.3 (56.0)	4.4 (39.1)	3.8 (33.8)	14.5 (128.9)	0 (0)
	SED	0.096	2.99	3.05	1.65	2.16	2.74		

maize receiving no additions. Uptake of soil N by millet crops was similar across different treatments (29 kg N ha^{-1}, on average).

Recovery of fertilizer N in soil

At maize harvest an average of 58% of the applied fertilizer N was recovered in the 0- to 60-cm layer, which increased to 76% by millet harvest. Fertilizer N recovery at the end of the rotation (i.e. after the millet harvest) was greater at Dordor Gaun (16.7±1.93 kg N ha^{-1}) than at Pakhribas (14.3±3.02 kg N ha^{-1}) though this difference was not significant. There was no significant effect of different N addition rates or the presence or absence of manure on the recovery of fertilizer N in any soil layer, except in the 0- to 20-cm layer at maize harvest where recoveries were greater in treatments receiving fertilizer alone than in plots amended with fertilizer plus manure (Table 4). Recovery of fertilizer N was generally greatest in the 0- to 20-cm layer at both harvests and decreased with depth. However, the cumulative fertilizer N recovery below 20 cm was greater than that in the 0- to 20-cm layer.

Fertilizer unaccounted for

On average, 28% of the applied N could not be accounted for in the crop or 0- to 60-cm soil layer at either location at maize harvest (Table 4). The amount of N unaccounted for increased as the N application rate increased and was also greater when fertilizer was applied in combination with manure (19.5 kg N ha^{-1}, on average) rather than alone (14.4 kg N ha^{-1}, on average). Similar patterns were also seen at millet harvest (Table 5) where on average 27% of the applied N could not be accounted for in the crop or the 0- to 60-cm soil layer. The amount of N unaccounted for also increased as the N application rate to the preceding maize crop increased and also when fertilizer was applied together with manure (18.4 kg N ha^{-1}, on average) rather than alone (16.2 kg N ha^{-1}, on average).

Short-term recovery of applied N fertilizer

Total recovery of applied fertilizer N in the 0- to 25-cm layer increased from 55±4.7% at application to 83±7.8% at day 1 (Fig. 2). It then decreased steadily to 53±9.6% at day 7. Urea was only present in the 0- to 5-cm layer immediately after application (9.3±0.78 μg N g^{-1}) and recovery of mineral N forms increased from approximately 10% to >50±6.4% by day 2 after application. Most of this recovered fertilizer N was NH_4^+ (30.8±6.29 μg N g^{-1}) rather than NO_3^- (2.4±1.22 μg g^{-1}) and much of it was in the 0- to 5-cm layer. The recovery as mineral N declined to 12% by day 4, and remained unchanged until day 7. Again, most of this mineral N was NH_4^+ (5.8±2.15 μg g^{-1}) rather than NO_3^- (1.9±0.80 μg g^{-1}). Recovery of fertilizer N in mineral N forms was negligible (<0.6%) in the 15- to 25-cm layer throughout the experiment.

The recovery of fertilizer N in organic N forms increased from 30±5.0% immediately, to 50±12.4% by day 4. Except initially, more of the fertilizer N in this pool was found beneath the 0- to 5-cm layer, so that averaging over days 4 and 7 the percentage recovery of fertilizer N in organic forms was 8.3±1.74% in the 0- to 5-cm layer and 37.7±5.77% in the 5- to 25-cm layer.

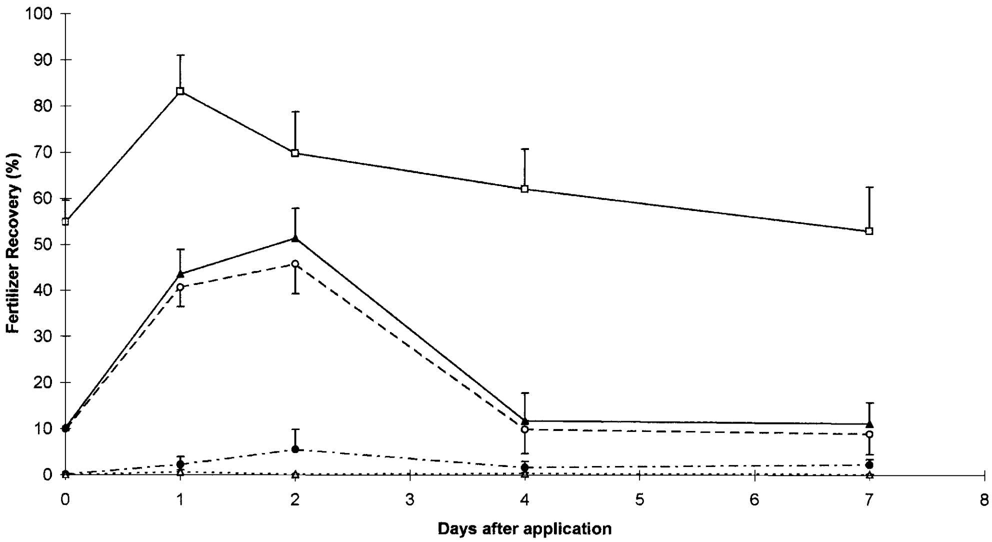

Fig. 2 Mean percentage recovery in mineral N forms in three soil layers (○, 0–5 cm; ●, 5–15 cm; △, 15–25 cm) of ^{15}N-labelled urea applied to small cores at Pakhribas in June 1998. ▲ represent the recovery in the total mineral N pool while □ represent the recovery in the total soil N pool. *Bars* represent a SEM

Discussion

The average grain yields of maize for all treatments in this experiment were 1,822 kg ha^{-1} for Pakhribas and 1,132 kg ha^{-1} for Dordor Gaun. These were less than those reported for 1997 (Pilbeam et al. 1999) at the same locations. Moreover, the yields were also approximately 800 kg ha^{-1} less than an 8-year average for maize grown at ARS-Pakhribas (Sherchan et al. 1999) and less than the 3.5 t ha^{-1} reported for yields of maize grown in on-farm experiments in western Nepal (Subedi and Dhital 1997). In contrast, yields of millet (1,783 kg ha^{-1}, on average at Pakhribas) were similar to the long-term average at Pakhribas (1,760 kg ha^{-1}; Sherchan et al. 1999) and to the average millet yield from the same location in the previous season (Pilbeam et al. 1999). The greater yields at Pakhribas compared to those at Dordor Gaun may be attributable to the greater content of soil organic matter and higher soil pH at Pakhribas, which, in turn, may reflect the previous management of the sites. The site at Dordor Gaun had been rented on an annual basis by the landowner to other tenant farmers who made few applications of nutrients, whereas the site at Pakhribas had been actively managed by the landowner. Nevertheless, the fertility of the soil in respect of N at both locations is low. According to Landon (1984) total N contents of <0.1% constitute very low amounts of soil N; soils at both sites were in this category. Moreover, 55% of sampled sites in the Western Region of Nepal had low total soil N levels (i.e. <0.2% N; Turton et al. 1995). The amounts of available P (21 mg kg^{-1} and 31 mg kg^{-1} at Pakhribas and Dordor Gaun, respectively) appear to be high (i.e. >15 mg kg^{-1} according to Landon 1984), but relative to the mean of 153±8.6 mg kg^{-1} reported by Turton et al. (1995) for soils in the Western Region of Nepal they are low. Furthermore, at both sites grain yields of maize responded more to inputs of fertilizer where nutrients were more readily available than to inputs of manure. This result is the same as that obtained in the previous season at these locations (Pilbeam et al. 1999), but contrasts with the general conclusion of a long-term experiment reported by Sherchan et al. (1999). They found that, over an 8-year experiment, average grain yields of maize and millet were greatest when both manure and fertilizer had been applied and lowest where fertilizer alone had been applied. However, crops given fertilizer yielded more than crops given only manure in the first 3 years.

Both the isotopic and the difference methods (Harmsen and Moraghan 1988) may be used to calculate the recovery of N fertilizer by the maize crop (Fig. 3). In both cases the recovery of N fertilizer was <25% and often considerably less. Such low recoveries of applied ^{15}N-labelled fertilizer are not uncommon in other locations. For example the recovery of ^{15}N-labelled fertilizer was <30% for maize grown in lysimeters in Zimbabwe (Kamukondiwa and Bergström 1994), in Ohio (Chichester and Smith 1978), in microplots in Belgium (Khanif et al. 1984) and in Kenya (Pilbeam et al. 1995). Nevertheless there are locations where recoveries of fertilizer by maize are much larger (>40%), for example Griffith, NSW, Australia (Mosier et al. 1986) and parts of the USA (West Virginia, Legg et al. 1979; Kentucky, Kitur et al. 1984; Nebraska, Walters and Malzer 1990). Such large differences between locations have also been reported for wheat (Pilbeam 1996), and in that case the difference between locations was attributed to differences in annual precipitation and potential evaporation, and the effect these may have on shoot:root ratio and the C/N composition of the crop residues.

The ^{15}N-fertilizer recovered in these experiments was distributed down the measured soil profile implying that fertilizer moved down the soil profile and was immobilized at depth. The rapid hydrolysis of urea (<1 day), coupled with the disappearance of ^{15}N-labelled mineral N pools in the surface layers and the appearance (<2 days) of ^{15}N-label in non-mineral N forms deeper in the profile show that movement and transformations of

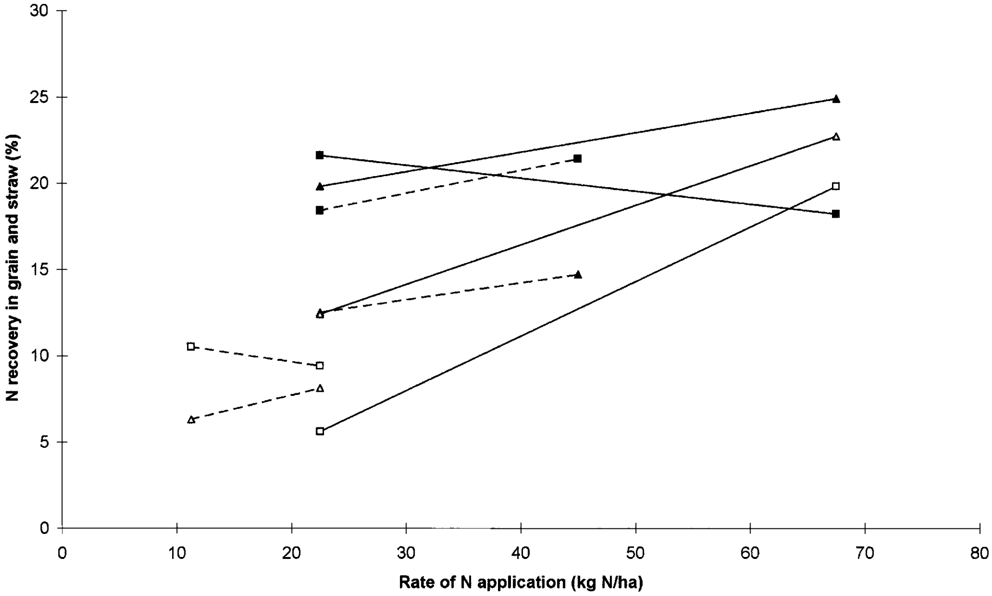

Fig. 3 N recovery (%) in the above-ground maize crop at harvest in 1998 calculated by the N difference method (*solid lines*) or by the isotope method (*dashed lines*) at Dordor Gaun (■, □) or Pakhribas (▲, △) where N was applied as fertilizer alone (*solid symbols*) or in combination with manure (*open symbols*)

N are rapid in these locations. In this experiment an average of 60% of the ^{15}N-labelled fertilizer recovered in the soil at harvest of maize was below 20 cm. This distribution is comparable with data for other studies with maize [e.g. Khanif et al. (1984) and Chichester and Smith (1978)] in which >85% of the total N recovered in the soil at harvest was below 30 cm. Sanchez and Blackmer (1988) also found that >65% of the ^{15}N-labelled fertilizer in mineral N forms at maize harvest was below 24 cm. This distribution differs from that found in a range of studies conducted elsewhere with wheat (Pilbeam 1996) which showed that >70% of ^{15}N-labelled fertilizer in the soil at harvest was above 20 cm. This perhaps suggests that crop type in addition to site or climate may also determine the distribution of N fertilizer in the soil profile.

A N balance (Tables 4, 5) for this experiment showed that some of the fertilizer N could not be accounted for in the crop and 0- to 60-cm soil layer at harvest and was presumed lost, or in the soil below 60 cm. Losses averaged 28%, but ranged from 0 to 68%. Similarly large percentage losses occurred in eastern England when fertilizer was applied to soils experiencing little or no moisture deficit in the autumn (Powlson et al. 1986). The soils at these sites in Nepal were at or near to field capacity prior to the top-dressing of N fertilizer (Pilbeam unpublished data). It is likely that high rainfall (>300 mm at both locations in each of June, July and August) will leach N deep into the profile, and almost certainly below the depth of sampling. Given the moisture content of the soil it is probable that anaerobic microsites occur, and that denitrification is possible. However, the experiment investigating the short-term recovery of applied fertilizer showed that while NO_3^- levels in the soil solution were spatially variable they were rarely >0.5 µg g^{-1}, and often considerably less. The enrichment of this NO_3^- pool was also low and little of the applied fertilizer was found as NO_3^- in the soil. Losses of N by denitrification therefore may be small.

Recovery of residual ^{15}N-labelled fertilizer in a second crop is generally <5%, irrespective of crop type or location, for example barley grown in the UK (Dowdell et al. 1984), wheat grown in the UK (Hart et al. 1993) and Oklahoma (Raun et al. 1999), and maize grown in Iowa (Sanchez and Blackmer 1988). In the present study, the recovery of ^{15}N-labelled fertilizer by millet was <3%. Clearly, the rate of turnover of immobilized fertilizer N is universally low and contributes little to the crop N uptake. Less than 1 kg N ha^{-1} was recovered in the millet crop in the experiments reported here. Recovery of ^{15}N-labelled fertilizer N in the soil after the harvest of the second crop ought to be less than that after the harvest of the first crop, by an amount of N equal to that removed in the second crop. Such low recoveries in the second crop, however, make measurements of such small changes in soil N problematic. It is not uncommon for the amount of label remaining in the soil to increase from one sampling to another, especially after applications of <100 kg N ha^{-1} (Hart et al. 1993; Pilbeam et al. 1997). This also occurred in this experiment. No definite explanation can be given for the observation, although it is possible that upward water movement during the growth of the millet crop also moved mineralized N upward, and that ^{15}N was taken up from beneath 60 cm by millet roots and then released into the sampled zone.

In conclusion, bari-land in the mid-hills of Nepal requires inputs of N to increase current crop production. This is most conveniently achieved in any single season by applying chemical fertilizer, but the benefits of fertilizer application are restricted to the season of application. Sustainable yield increases might be achieved if farmers in the mid-hills of Nepal combine basal applications of manure with top-dressings of N fertilizer.

Acknowledgements This publication is an output from project R6757 funded by the UK Department for International Development (DFID) for the benefit of developing countries. The views expressed are not necessarily those of DFID. We thank the technical staff at ARS-Lumle and ARS-Pakhribas for excellent technical assistance, and Ms D. Hutchison for analysis of the ^{15}N-labelled samples.

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