Multiseason Recoveries of Organic and Inorganic Nitrogen-15 in Tropical Cropping Systems

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In tropical agroecosystems, limited N availability remains a major impediment to increasing yield. A ^{15}N-recovery experiment was conducted in 13 diverse tropical agroecosystems. The objectives were to determine the total recovery of one single ^{15}N application of inorganic or organic N during three to six growing seasons and to establish whether the losses of N are governed by universal principles. Between 7 and 58% (average of 21%) of crop N uptake during the first growing season was derived from fertilizer. On average, 79% of crop N was derived from the soil. When ^{15}N-labeled residues were applied, in the first growing season 4% of crop N was derived from the residues. Average recoveries of ^{15}N-labeled fertilizer and residue in crops after the first growing season were 33 and 7%, respectively. Corresponding recoveries in the soil were 38 and 71%. An additional 6% of the fertilizer and 9.1% of the residue was recovered by crops during subsequent growing seasons. There were no significant differences in total ^{15}N recovery (average 54%) between N from fertilizer and N from residue. After five growing seasons, more residue N (40%) than fertilizer N (18%) was recovered in the soil, better sustaining the soil organic matter N content. Long-term total recoveries of ^{15}N-labeled fertilizer or residue in the crop and soil were similar. Soil N remained the primary source of N for crops. As higher rainfall and temperature tend to cause higher ^{15}N losses, management practices to improve N use efficiency and reduce losses in wet tropical regions will remain a challenge.

Abbreviations: FUE, fertilizer use efficiency; NUE, nitrogen use efficiency; SOM, soil organic matter.

There is growing concern about the long-term sustainability and high environmental costs of agroecosystems in developed and developing countries (Robertson and Paul, 1998; Galloway et al., 2008). To achieve the targets of long-term sustainability and minimized environmental impact of agroecosystems, whole-ecosystem nutrient use efficiency—the amount of plant growth per unit N added to the system—and C cycling needs to be better understood and subsequently managed (Cassman et al., 2003). As Robertson and Paul (1998) pointed out so elegantly, the application of modern ecosystem concepts to farming systems forms a frontier in ecosystem science that will benefit both ecosystem theory and agroecosystem management.

World population is expected to increase from its current 6.7 billion to 8 billion by about 2020. The vast majority of the expected increase in population will occur in the less developed world, particularly in Asia (Pinstrup-Anderson et al., 1999). Moreover, increased prosperity causes diets to become more meat based, leading to a higher demand for grain production and the need for N fertilizers and better management (Cassman et al., 2002; Gilland, 2002). The worldwide production of fertilizer N in 2006 was calculated at 100 Tg (FAO, 2008) and is projected to increase to >135 Tg yr^{-1} by 2030 (Galloway et al., 1994). If fertilizer use efficiency (FUE) would not further increase, the production of fertilizer N would have to increase by one-third to feed the world, without a change in diet. Such an increase has major implications for greenhouse gas emissions from a combination of energy to manufacture N fertilizer (with associated emissions of CO_2) and N_2O emissions from the use of N fertilizer.

It is commonly found that only 30 to 50% of fertilizer N is taken up by the crop in the first growing season (Tillman et al., 2002; Ladha et al., 2005). The fertilizer N not taken up by the crop either becomes incorporated into the soil

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organic matter (SOM) or is lost. Losses occur mainly as leaching, denitrification, or volatilization and cause potential environmental harm, affecting ecosystem functioning (Tillman, 1999).

Nitrogen can be applied to crops through inorganic fertilizer, through organic N in the form of manure or crop residues, or as a combination of both organic and inorganic N (Vanlauwe et al., 2001). Arguments can be made that if N is applied as organic rather than inorganic forms, short-term N losses should be lower. When N is applied as residue N, it can remain immobilized, which can lead to reduced N losses via leaching and denitrification (Robertson, 1997; Scow, 1997); however, synchronization of the release of residue N and the demand for N by the crop becomes an important factor (Becker et al., 1994; Myers et al., 1994). Because fertilizer N is much more readily available for crop uptake, better synchronization of the N supply with crop demand can be achieved, tending to minimize N losses. A good synchronization of N released from organic sources and the demand for N by the crop is more difficult to achieve. Net mineralization of organic N residues and uptake by the crop are processes governed by the C/N ratio of the residue and its lignin content (Melillo et al., 1982), its polyphenolic content (Palm and Sanchez, 1990), the climate (Jenkinson and Ayanaba, 1977), and the soil type (Campbell, 1978). Complex interactions exist among the numerous factors that control the rate of decomposition. Therefore, optimal synchronization of the release of N from organic residues with crop N demand remains a challenge (Groffman et al., 1987).

Soil organic matter has the ability to store nutrients and improve soil structure, and has long been used as a key indicator of sustainability of a cropping system (Paustian et al., 1997). Results from long-term cropping system studies show that SOM and total soil N content can be increased by applying organic N (Glendining et al., 1997; Peters et al., 1997; Jenkinson, 2001).

Nitrogen-15-labeled material can be used in short-term studies imposed on long-term cropping system experiments to follow the flow and fate of N (Powlson et al., 1986; Powlson, 1994). The use of a ^{15}N tracer permits the detection and quantification of applied N in various sinks, including the crop, available soil N, or SOM N pools (Powlson and Barraclough, 1993). It also allows determination of the amount of applied N lost from the system, a key indicator of cropping system N use efficiency.

It is of interest to determine whether, in studies that encompass several growing seasons, the recovery of organic and inorganic N is an indication of the long-term N retention patterns in various cropping systems. If such studies accurately reflect long-term trends, new management practices can be evaluated more quickly for their effect on cropping system N use efficiency, expediting adoption if warranted.

We conducted an extensive ^{15}N tracer recovery experiment using inorganic and organic N sources for three to six growing seasons in diverse agroecosystems and climatic zones located on three continents in nine countries. The main objectives of the study were to: (i) determine the total recovery of applied inorganic and organic ^{15}N in the crop and soil in diverse agroecosystems and eco-zones; (ii) establish whether the recovery and losses of organic and inorganic N are governed by universal principles and follow similar patterns independent of the agroecosystem tested or its eco-zone; (iii) determine the residual effect of inorganic and organic N sources on ^{15}N uptake by crops during subsequent growing seasons; and (iv) determine if residue management practices following ^{15}N-labeled fertilizer application affect the recovery and losses of ^{15}N. To follow the fate of applied fertilizer, ^{15}N-labeled fertilizer was applied and followed in the crop and soil for several growing seasons, with crop residues either removed or incorporated. For comparison with fertilizer N, ^{15}N-labeled crop residues were generated under field conditions and the recovery of organically applied ^{15}N followed for several growing seasons.

MATERIALS AND METHODS

A long-term coordinated research project on the management of organic matter and N cycling, using ^{15}N-isotope techniques, was established in 1996 by the International Atomic Energy Agency (IAEA) and the Food and Agricultural Organization of the United Nations. Experiments were initiated in nine countries at 13 experimental sites, which covered a diverse range of climatic regions, soil orders, soil characteristics, and cropping systems (Tables 1 and 2). With the exception of Chile, all experiments were conducted under tropical environments. Precipitation among the 13 sites ranged from a low of 85 mm (Morocco) to a high of 2100 mm (Sri Lanka). Mean annual temperatures ranged between 14 and 30°C. In total, 10 different crops were included in the study (Table 2). Soil pH ranged from acid to alkaline and total organic C ranged from 1 to 30 g kg^{-1} of soil. Soil texture covered the entire spectrum from sandy to clay. Plant-available P was assessed using the standard methods used in each country and considered appropriate for the soil type, environment, and cropping system on the basis of previous local studies. Plant-available P was judged to be adequate and not likely to be a constraint to crop growth or N use. Mineral N across all sites ranged from a low of 8 mg kg^{-1} to a high of 113 mg kg^{-1}. All soil analyses with the exception of total N and C were performed in the various countries following protocols described elsewhere (Keeney and Nelson, 1982; Knudsen et al., 1982; McLean, 1982; Olson and Sommers, 1982; Rhoades, 1982).

At all 13 experimental sites, a similar ^{15}N-labeling field experiment was performed, the experimental period being determined by (i) the rate of dilution of the applied ^{15}N, and (ii) the number of crops grown per year.

The flow of ^{15}N in the soil and crop N pools was determined following the application of ^{15}N as a single application of ^{15}N-labeled fertilizer or as ^{15}N-labeled residue. At all 13 sites, two concurrent experiments were conducted. In the first experiment, the impact of residue removal on the recovery of ^{15}N-labeled fertilizer in the crop and soil was assessed. In a second experiment, the recovery of N from ^{15}N-labeled residue in the crop and soil was followed. With the one exception of replacing common bean (*Phaseolus vulgaris* L.) and barley (*Hordeum vulgare* L.) with red clover (*Trifolium pratense* L.) in Chile, the same crop rotations were used for both experiments at all sites (Table 2). Other crops grown at the various sites were rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L. ssp. *aestivum*), sugarcane (*Saccharum officinarum* L.), maize (*Zea mays* L.), peanut (*Arachis hypogaea* L.), mungbean (*Phaseolus aureus* Roxb.), and sunflower (*Helianthus annuus* L.).

A key purpose of the experiments was to follow how much of the ^{15}N label applied as inorganic or organic N was recovered by the crop. Therefore,

Table 1. Geographical location and soil and climatic information for the 13 locations used in the ^{15}N-labeled fertilizer and ^{15}N-labeled residues study.

Country	Location	Soil order	pH	Soil organic C	Soil total N	Mineral			CEC†	Bulk density	Sand	Silt	Clay	*T*‡	Precipitation
						N	P	K							
				—— g kg^{-1} ——		– mg kg^{-1} –		– cmol kg^{-1} –		Mg m^{-3}	——— % ———			°C	mm
Bangladesh	Mymensingh	Haplaquepts	6.1	12.0	0.80	NA§	13	0.20	10.6	1.38	49	38	13	NA	NA
Brazil	Piracicaba	Ultisol	5.0	12.0	1.20	8	27	0.32	10.2	1.35	29	16	55	21	1253
Chile	Santa Rosa	Andisol	5.2	8.7	0.46	113	11	0.17	7.1	1.08	73	23	3	14	1042
		Andisol	5.8	9.0	0.43	58	12	0.33	7.2	1.08	73	23	3	14	1042
China	Hangzhou	Inceptisol	6.9	16.8	1.99	33	145	0.30	13.8	1.06	42	38	20	17	1500
Egypt	Minia	Entisol	8.1	1.1	0.14	9	4	0.37	4.0	1.68	87	9	4	22	NA
Malaysia	Puchong	Ultisol	5.3	16.6	1.77	8	13	0.12	6.9	1.28	62	4	34	31	1800
Morocco	Tafilalet	Aridisol	8.4	9.7	0.69	9	9	0.01	9.2	1.28	36	48	16	18	85
	Central Morocco	Inceptisol	8.4	30.0	1.20	11	10	1.39	6.0	1.35	16	52	32	17	618
	Atlas	Inceptisol	7.8	19.0	0.90	11	56	0.24	5.8	1.39	92	9	0	20	495
Sri Lanka	Kundasala	Ultisol	6.4	8.3	1.40	14	61	0.32	5.1	1.41	29	46	25	30	2100
		Ultisol	6.4	8.3	1.40	14	61	0.32	5.1	1.41	29	46	25	30	2100
Vietnam	Ba Ria Vung Tau	Ultisol	4.9	4.6	0.78	22	49	0.25	7.6	1.38	52	8	40	28	1643

† Mineral N, P, and K.

‡ Mean annual temperature.

§ NA, information was not available.

recycling of ^{15}N in the residues was avoided by removing ^{15}N-labeled residue and replacing it with an equal amount of unlabeled residue generated at an adjacent site. As recycling of ^{15}N present in the roots and subsequent uptake by the following crop could not be avoided, no separation between ^{15}N derived from the roots or from soil organic matter including mineral N can be made. In general, the size of the individual experimental plots was 8 by 20 m. At all sites, the experimental treatments were laid out as a randomized complete block, replicated four times.

The overall experiment consisted of three treatments:

> Treatment 1: a single application of ^{15}N-fertilizer in Year 1, in which the aboveground crop residue that became labeled with ^{15}N during the subsequent growing seasons was replaced by unlabeled residue. Unlabeled fertilizer N was applied at recommended rates for the following crops and growing seasons.
>
> Treatment 2: a single application of ^{15}N-labeled fertilizer, the removal of all aboveground residues throughout the experiment, and application of unlabeled fertilizer N at recommended rates for the following crops.
>
> Treatment 3: a single application of ^{15}N-labeled residue. The subsequently produced residues that became labeled with ^{15}N were replaced by unlabeled residue. Inorganic fertilizer was applied in the season in which the ^{15}N-labeled residues were applied and for all subsequent crops at recommended rates.

Table 2. Cropping sequence, agronomic, and ^{15}N application information for the 13 locations studied.

Country	Location	Crop sequence†	Crops grown	^{15}N fertilizer			^{15}N residue			
				Type	N rate	^{15}N content	Amount	N rate	C/N ratio	^{15}N content
			no.		kg N ha^{-1}	^{15}N excess	— kg ha^{-1} —			^{15}N excess
Bangladesh	Mymensingh	*wheat*–rice	6	$(NH_4)_2SO_4$	60	10.5	5000	46	50	3.57
Brazil	Piracicaba	*sugarcane*–ratoon	3	$(NH_4)_2SO_4$	63	11.7	18550	127	100	1.80
Chile	Santa Rosa	*maize*–wheat–bean–red clover	4	Urea	300	5.1	8000	39	87	1.94
		wheat–bean–barley	3	$(NH_4)_2SO_4$	160	6.7	4000	12	141	4.35
China	Hangzhou	*rice*–wheat	6	$(NH_4)_2SO_4$	150	9.9	9458	160	24	0.68
Egypt	Minia	*wheat*–peanut	6	$(NH_4)_2SO_4$	60	9.8	3125	44	63	1.94
Malaysia	Puchong	*maize*–peanut	4	$(NH_4)_2SO_4$	60	9.8	2733	38	58	1.80
Morocco	Tafilalet	*wheat*–wheat	4	$(NH_4)_2SO_4$	28	9.8	4780	149	12	1.92
	Central Morocco	*sunflower*–wheat	5	$(NH_4)_2SO_4$	35	10.0	7500	129	22	0.74
	Atlas	*bean*–wheat	3	$(NH_4)_2SO_4$	20	9.8	4500	223	7	0.70
Sri Lanka	Kundasala	*maize*–mungbean‡	6	$(NH_4)_2SO_4$	80	9.8	7100	70	25	1.98
		maize–mungbean	5	$(NH_4)_2SO_4$	80	9.8	5800	46	29	0.99
Vietnam	Ba Ria Vung Tau	*maize*–mungbean	4	$(NH_4)_2SO_4$	120	5.4	3214	31	45	3.08

† ^{15}N-labeled crop residue that was reapplied is italicized.

‡ The first maize–mungbean crop rotation started in the dry season whereas the second rotation started in the wet season.

As the ^{15}N-labeled residues generated in the first growing season in Treatment 1 were used as the source of the ^{15}N-labeled residue for Treatment 3, the experiment to follow the fate and recovery of ^{15}N residue started in the second growing season. Likewise, the comparison of residue incorporation vs. removal (Treatment 1 vs. Treatment 2) also started in the second growing season. For the first growing season, Treatments 1 and 2 were identical because removal or retention of residues started after the harvest of the first crop. Hence, the results for Treatments 1 and 2 from the first growing season were combined and used to calculate ^{15}N recovery in the season of application.

Caution is required in making a direct comparison between the recovery of ^{15}N residues and ^{15}N fertilizer at a specific site. Although a similar crop rotation was used when the ^{15}N material was applied, the climatic growing conditions during the first growing season when the ^{15}N fertilizer was applied may not have been identical to the second growing season, when the ^{15}N residue (generated in the first growing season) was applied. Therefore, only comparisons of the average recovery of residues and fertilizer ^{15}N across all sites have been made. As a relatively large number of experimental sites was used, any effect on ^{15}N recovery of differences in weather among the growing seasons should be minimal when considering the average across sites.

Labeled ^{15}N fertilizer was applied to a ^{15}N microplot located in the center of the larger experimental plot at the onset of the experiment. For details regarding rates of ^{15}N fertilizer applied, its form, and its ^{15}N enrichment, see Table 2. The ^{15}N fertilizer was applied in four splits: 25% of the total amount at seeding, 25% 2 wk after seeding; 25% 4 wk after seeding; and the final 25% 6 wk after seeding. The main purpose of applying the ^{15}N in four doses was to maximize ^{15}N uptake by the crop and to generate uniformly ^{15}N-labeled residue to be used for the second experiment. It is probable that this splitting of the ^{15}N fertilizer applications would have led to somewhat smaller N losses than is usual in the cropping systems studied. The ^{15}N microplots were mostly between 3 by 3 and 4 by 4 m, depending on the row spacing of the different cropping systems, and always included border rows that were not used for ^{15}N analysis. Fairly large ^{15}N microplots were used because of the duration of the experiment, the number of plant and soil samples to be collected during the experimental period, and the risk of soil movement and edge effects. At maturity of the first crop, the ^{15}N-labeled residue from Treatment 1 was used to follow the fate of ^{15}N from residue in a similar cropping system. The quantities of ^{15}N-labeled residue applied are reported in Table 2, along with the corresponding ^{15}N enrichment and the C/N ratio. Additional information can be found elsewhere concerning the experimental design and site characteristics in China, Morocco, Brazil, and Malaysia (Wang et al., 2002; Ichir and Ismaili, 2002; Basanta et al., 2003; Ichir et al., 2003; Mubarak et al., 2003a,b). Due to the disappearance of the ^{15}N enrichment, not every experiment could be continued beyond the third growing season.

At each crop maturity, the total aboveground yield, i.e., grain and residue, was determined using standard practices and described elsewhere (Wang et al., 2002; Ichir and Ismaili, 2002; Basanta et al., 2003; Ichir et al., 2003; Mubarak et al., 2003a,b). Briefly, plants were harvested at physiological maturity, dried at 60°C to constant weight, and a weight measurement taken. The size of the plot harvested for determining yield was 9 m^2 or larger. A subsample of the grain and residue was collected and its N content and the ^{15}N isotopic composition of both grain and residue determined individually using an automatic elemental N analyzer coupled to a SIRA 9 (ANA-SIRA) mass spectrometer at the IAEA Analytical Laboratory at Seibersdorf, Austria (Axman, 1990). The N content and isotopic composition of the sugarcane were analyzed for total N and for ^{15}N/^{14}N isotope ratio using a mass spectrometer (ANCA-SL, Europa Scientific, Crewe, UK) located at the University of Sao Paulo at Piracicaba, Brazil (Barrie and Prosser, 1996).

Soil samples were taken in increments of 0 to 15, 15 to 30, and 30 to 50 cm for estimation of bulk density and analysis of total N and ^{15}N isotopic composition. In general, four samples were taken from the center of a single ^{15}N microplot and combined for analysis.

Calculations

Since the amount of ^{15}N added, either as N fertilizer or crop residues, varied by cropping system, relative values of ^{15}N recovery in the crop, soil, and crop–soil system were calculated as

$$N_{k,j,s} = \frac{\mathrm{ANE}_{k,j}}{\mathrm{ANE}_s}\frac{\mathrm{QN}_{k,j}}{\mathrm{QNA}_s}100 \qquad [1]$$

where $N_{k,j}$ is the recovery of ^{15}N (%) in the soil (Compartment 1, $k = 1$) or N recovered by the crop (Compartment 2, $k = 2$), at the end of the jth crop cycle ($j = 1, 2, 3, ..., n$), after a single addition of N to the soil via the source s ($s = 1$ for fertilizer or $s = 2$ for crop residue); $\mathrm{ANE}_{k,j}$ is the atom % ^{15}N excess in the kth compartment ($k = 1$ or 2) at the end of the jth crop cycle; ANE_s is the atom % ^{15}N excess in the source s; $\mathrm{QN}_{k,j}$ is the quantity of N in the kth compartment ($k = 1$ or 2) (kg ha^{-1}) at the end of the jth crop cycle; QNA_s is the quantity of N applied via the source s (kg ha^{-1}); and k (compartment) is soil ($k = 1$), crop ($k = 2$), or soil + crop ($k = 3$)—in the calculations, each compartment was divided into subcompartments (for the soil, 0–15, 15–30, and 30–50-cm soil layers; for the crop, plant parts, such as grains, stubbles, etc.).

The correction factor for calculating the atom % ^{15}N excess was based on the atom % ^{15}N value of unlabeled plant components or soil:

$$\mathrm{Nc}_{2,j} = \sum_{i=1}^{j} N_{2,i} \qquad [2]$$

where $\mathrm{Nc}_{2,j}$ is the cumulative percentage of N taken up by the crop ($k = 2$) from the ith to the jth cycle, and

$$N_{3,j} = N_{1,j} + \mathrm{Nc}_{2,j} \qquad [3]$$

where $N_{3,j}$ is the ^{15}N recovery (%) in the crop–soil system ($k = 3$), from the ith to the jth crop cycle.

Nitrogen losses from the crop–soil system were calculated as the deficit in % ^{15}N recovery, according to

$$\mathrm{Nl}_{3,j} = 100 - N_{3,j} \qquad [4]$$

where $\mathrm{Nl}_{3,j}$ is the N losses (%) in the crop–soil system ($k = 3$), from the ith to the jth crop cycle.

Statistical Analyses

Analyses were conducted with the PROC MIXED procedure of SAS (Littel et al., 1996), with block and location as random effects and cropping cycles and treatment as fixed effects. The model was also pa-

Table 3. Total aboveground yield, N accumulation and contribution in the first growing season of fertilizer-N, residue-N and soil mineral for crops grown in a diverse array of cropping systems, soil and climatic conditions.

Country	Crop	N Applied	Aboveground biomass	Total crop N	Derived from fertilizer N		NUE†	Derived from soil N	
		kg N ha^{-1}	Mg ha^{-1}	——— kg N ha^{-1}———		————— %—————		kg N ha^{-1}	%
^{15}N-labeled fertilizer‡									
Bangladesh	wheat	60	6.1 ± 0.1§	60 ± 3	26 ± 2	43 ± 1	43 ± 3	34 ± 1	57 ± 1
Brazil	sugarcane–ratoon	63	48.8 ± 1.1	251 ± 7	40 ± 2	16 ± 1	63 ± 3	211 ± 6	84 ± 1
Chile	maize	300	18.8 ± 1.1	178 ± 7	55 ± 1	31 ± 2	34 ± 1	123 ± 8	69 ± 2
Chile	wheat	160	13.2 ± 0.5	124 ± 4	20 ± 2	16 ± 2	7 ± 1	104 ± 5	84 ± 2
China	rice	60	17.9 ± 0.3	292 ± 7	20 ± 2	7 ± <1	33 ± 3	272 ± 6	93 ± <1
Egypt	wheat	60	5.1 ± 0.2	80 ± 6	16 ± 1	20 ± 1	26 ± 2	64 ± 5	80 ± 1
Malaysia	maize	60	3.4 ± 0.1	53 ± 2	12 ± 1	23 ± 1	20 ± 1	41 ± 2	77 ± 1
Morocco	wheat	42	8.2 ± 0.7	161 ± 7	29 ± 2	18 ± 1	34 ± 3	133 ± 7	82 ± 1
Morocco	sunflower	35	9.4 ± 0.3	129 ± 7	9 ± 1	7 ± <1	27 ± 2	119 ± 7	93 ± <1
Morocco	bean	85	6.9 ± 0.1	225 ± 6	16 ± <1	7 ± <1	38 ± 1	209 ± 6	93 ± <1
Sri Lanka	maize	60	10.6 ± 0.1	139 ± 6	15 ± 1	11 ± <1	25 ± 2	124 ± 5	89 ± <1
Sri Lanka	maize	60	10.6 ± 0.1	139 ± 6	25 ± 1	18 ± 1	42 ± 2	114 ± 6	82 ± 1
Vietnam	maize	120	7.2 ± 0.3	92 ± 3	53 ± 2	58 ± 1	44 ± 1	39 ± 2	42 ± 1
Mean			12.7 ± 0.4	147 ± 6	26 ± 1	21 ± 1	33 ± 2	122 ± 6	79 ± 1
^{15}N-labeled residues¶									
Bangladesh	wheat	46	14.0 ± 0.1	156 ± 4	10 ± 4	6 ± 3	17 ± 7	146 ± 5#	94 ± 3
Brazil	sugarcane–ratoon	127	58.1 ± 0.7	196 ± 4	4 ± <1	2 ± 0	6 ± 1	192 ± 4	98 ± <1
Chile	maize	39	6.3 ± 0.6	56 ± 5	<1 ± <1	<1 ± <1	<1 ± <1	56 ± 5	100 ± <1
Chile	wheat	12	1.7 ± 0.1	35 ± 4	1 ± <1	1 ± <1	<1 ± <1	34 ± 4	99 ± 1
China	rice	160	3.9 ± 0.3	42 ± 3	5 ± <1	12 ± 1	8 ± <1	37 ± 4	88 ± 1
Egypt	wheat	36	5.2 ± 0.6	132 ± 17	1 ± <1	1 ± <1	2 ± <1	130 ± 17	99 ± <1
Malaysia	maize	38	4.4 ± 0.4	110 ± 7	2 ± <1	2 ± <1	4 ± <1	108 ± 7	98 ± <1
Morocco	wheat	223	14.1 ± 1.0	217 ± 11	9 ± 1	4 ± <1	10 ± 1	208 ± 11	96 ± <1
Morocco	sunflower	129	11.5 ± 0.6	160 ± 12	11 ± 2	7 ± 1	31 ± 5	149 ± 10	93 ± 1
Morocco	bean	149	8.2 ± 0.1	72 ± 7	7 ± 1	10 ± 1	17 ± 2	65 ± 7	90 ± 1
Sri Lanka	maize	70	4.4 ± 0.1	148 ± 2	1 ± <1	<1 ± <1	1 ± <1	147 ± 2	100 ± <1
Sri Lanka	maize	46	4.4 ± 0.1	160 ± 10	1 ± <1	<1 ± <1	1 ± <1	159 ± 10	100 ± <1
Vietnam	maize	31	0.8 ± 0.1	30 ± 2	2 ± <1	6 ± 1	1 ± <1	28 ± 2	94 ± 1
Mean			11.2 ± 0.3	127 ± 8	4 ± 1	4 ± 1	7 ± 1	123 ± 8	96 ± 1

† NUE, N in the crop derived from fertilizer (kg) divided by the amount of fertilizer N applied times 100.

‡ Average of ^{15}N-labeled fertilizer + residue and ^{15}N-labeled fertilizer – residue treatments.

§ Mean ± SE.

¶ Estimates derived from second crop cycle; all other estimates are derived from the first crop cycle.

Includes N from unlabelled fertilizer N.

rameterized to account for repeated measurements across cropping cycles for each experimental unit (plot) using the repeated statement with an appropriate covariance structure. Treatment effects were declared significant at $P < 0.05$ for all analyses.

An extension of the previous statistical model was implemented to assess location interactions for ^{15}N recovery (Littel et al., 2002). The model and data used for the analysis were the same, except for the inclusion of a covariable cross-classified with the fixed factor(s), and the analysis was conducted separately for each of the first three cropping cycles. Various climate and soil characteristic covariables (Table 1) were considered for this analysis on an individual basis. The goal of the analysis was to assess the sensitivity of ^{15}N recovery to the different climatic and edaphic conditions across locations; slope coefficients for ^{15}N recovery vs. a covariable were estimated for each management treatment. Responses for the ^{15}N fertilizer minus residue treatment were similar to those for the ^{15}N fertilizer plus residue treatment, thus are not shown. Slope coefficients were declared significant at $P < 0.05$ for all analyses.

Due to a reduced number of locations where the experiment was continued for more than three growing seasons, the amount of data available after the third growing season was too limited to carry out covariance analysis. Means and SE are presented for data collected beyond the third cropping cycle.

RESULTS AND DISCUSSION

Crop Yield and Total Nitrogen Accumulation

As expected, the total aboveground biomass varied widely among sites and crop species. Seasonal biomass accumulation was highest for sugarcane in Brazil (>48 Mg ha^{-1} in the first growing season where ^{15}N fertilizer had been applied; Table 3) and lowest for maize in Vietnam (0.7 Mg ha^{-1} where ^{15}N residues had been applied; Table 4). A large range in yield and total crop N also existed for the same species across location and growing season. For example, the yield of maize in the first growing season with ^{15}N fertilizer applied ranged from a low of 3.4 Mg ha^{-1} in Malaysia to a high of 10.6 Mg ha^{-1} in Sri Lanka (Table 3). A similarly large

Table 4. Total aboveground (grain, straw, residue, and chaff) yield and N accumulation in crops for the second and subsequent growing seasons at 13 locations.

Country	Location	Rotation	Crops grown	Treatment 1†		Treatment 2†		Treatment 3†	
				Total yield	Total N	Total yield	Total N	Total yield	Total N
			no.	Mg ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	kg N ha^{-1}	Mg ha^{-1}	kg N ha^{-1}
Bangladesh	Mymensingh	wheat	2	6.8 ± 0.2‡	61 ± 1	6.7 ± 0.4	56 ± 2	6.9 ± 0.2	64 ± 3
		rice	3	11.2 ± 0.1	100 ± 6	11.0 ± 0.1	93 ± 4	12.7 ± 0.2	113 ± 7
Brazil	Piracicaba	sugarcane	2	49.5 ± 2.3	156 ± 16	56.6 ± 1.4	192 ± 14	53.2 ± 2.0	181 ± 9
Chile	Santa Rosa	wheat	1	3.8 ± 0.3	32 ± 4	6.7 ± 0.7	51 ± 4	6.3 ± 0.6	56 ± 5
		red clover	2	NA§	NA	2.3 ± 0.6	63 ± 8	3.6 ± 0.6	101 ± 21
	Santa Rosa	bean	1	1.7 ± 0.1	35 ± 4	NA	NA	1.7 ± 0.1	35 ± 4
		barley	1	13.6 ± 0.4	128 ± 4	NA	NA	13.2 ± <0.1	123 ± 4
China	Hangzhou	wheat	3	8.5 ± 0.6	116 ± 9	7.5 ± 0.5	102 ± 10	5.5 ± 0.5	57 ± 5
		rice	2	9.6 ± 0.6	197 ± 9	8.8 ± 0.4	179 ± 10	8.3 ± 0.4	161 ± 5
Egypt	Minia	wheat	2	5.8 ± 0.4	126 ± 10	5.5 ± 0.2	119 ± 15	5.8 ± 0.3	137 ± 8
		peanut	3	3.8 ± 0.3	91 ± 8	3.9 ± 0.3	89 ± 7	4.0 ± 0.3	103 ± 9
Malaysia	Puchong	peanut	2	5.4 ± 0.5	127 ± 16	5.1 ± 0.1	125 ± 11	4.5 ± 0.4	110 ± 7
		maize	3	3.6 ± 0.4	55 ± 6	3.2 ± 0.3	51 ± 6	3.3 ± 0.2	50 ± 5
Morocco	Tafilalet	fababean	1	6.9 ± 0.6	215 ± 16	6.3 ± 1.0	194 ± 23	6.4 ± 0.4	196 ± 11
		wheat	1	7.3 ± 0.4	73 ± 9	9.1 ± 0.1	88 ± 10	8.2 ± 0.1	72 ± 7
	Central Morocco	wheat	1	11.0 ± 0.5	154 ± 13	11.6 ± 0.4	160 ± 6	11.5 ± 0.6	160 ± 12
		sunflower	1	10.6 ± 0.9	105 ± 17	10.7 ± 0.5	115 ± 12	10.0 ± 1.0	79 ± 3
	Atlas	wheat	2	11.3 ± 1.8	199 ± 36	9.7 ± 1.5	174 ± 25	10.6 ± 1.5	166 ± 21
Sri Lanka	Kundasala	maize	2	10.8 ± 0.1	134 ± 6	10.3 ± 0.1	129 ± 7	10.5 ± 0.1	127 ± 2
		mungbean	3	4.6 ± 0.1	149 ± 6	4.1 ± 0.1	131 ± 7	4.5 ± 0.1	148 ± 3
	Kundasala	maize	2	10.8 ± 0.1	134 ± 6	10.3 ± 0.1	129 ± 7	10.8 ± 0.1	125 ± 3
		mungbean	2	4.6 ± 0.1	149 ± 6	4.1 ± 0.1	131 ± 7	4.5 ± 0.1	149 ± 7
Vietnam	Ba Ria Vung Tau	maize	1	5.9 ± 0.3	81 ± 4	6.2 ± 0.3	95 ± 12	5.9 ± 0.3	95 ± 12
		soybean	2	0.8 ± 0.1	27 ± 2	0.7 ± <0.1	27 ± 2	0.8 ± <0.1	27 ± 1
Mean				9.1 ± 0.7	113 ± 4	9.0 ± 0.8	109 ± 4	9.3 ± 0.8	113 ± 4

† Treatment 1: ^{15}N-labeled fertilizer + residue; Treatment 2: ^{15}N-labeled fertilizer – residue; Treatment 3: ^{15}N-labeled residue.

‡ Mean ± SE.

§ NA, data not collected.

range, 1.7 to 14.1 Mg ha^{-1}, was also observed for the total aboveground biomass (grain plus straw) of wheat. This wide range in yield among sites reflects the length of the growing season (with between one and three crops per year) and differences in indigenous soil N supply, fertilizer-N input, and residue input, as well as differences in climate and soil type. Low yield in Vietnam and Malaysia in the first year of the experiment was caused by inclement weather during the early part of the growing season.

Soil as a Source of Nitrogen for Plants

Crop demand for N can be met by applying inorganic and organic sources of N or through N mineralization from SOM. Covering a diverse range of agroecosystems in tropical and subtropical climatic zones and across different soil types, these results show that soil N from the net N mineralization of SOM was the dominant source of N in the crops. On average, unlabeled N (presumed to come predominantly from soil N mineralization) accounted for 79% of the total N in the crop (Table 3) even though ^{15}N-labeled inorganic fertilizer in the range of 20 to 300 g N ha^{-1} had been applied. The quantities of N derived from soil were often large: >100 kg N ha^{-1} at nine of the 13 experimental sites and >200 kg N ha^{-1} at three sites (Brazil, China, and Morocco; Table 3). Even at the site with the lowest SOM content (Egypt, 1.1 g kg^{-1} soil organic C, 1.4 g kg^{-1} total soil N; Table 1), 64 kg N ha^{-1} was supplied from soil (mean of Treatments 1 and 2 in Table 3). In a few cases, these large values may be attributable to other sources of N; for example, in China it is likely that unlabeled N was derived from NO_3 in the irrigation water, NO_3 residues from previous excessive fertilizer N applications, and atmospheric deposition (Ju et al., 2006; Fang et al., 2008). Overall, however, the results emphasize the importance of SOM as a source of N for crops in most environments. Averaged across all sites, 25.8 kg N ha^{-1} was obtained from fertilizer-N sources, whereas soil sources provided, on average, 122 kg N ha^{-1} to the crop (Table 3).

In a detailed study conducted in a temperate zone, the contribution of unlabeled N sources, i.e., SOM plus wet and dry atmospheric deposition, as the source of N for plant growth was determined to be between 30 and 50% for a variety of crops grown across different growing seasons (Macdonald et al., 1997). Total crop N uptake from unlabeled sources was related to the size of the soil mineral N pool in the spring, which in turn was related to the total soil N content. For rice in Australia, SOM remained the major source of N and the crop accumulated up to 113 kg N ha^{-1}, even following the application of 140 kg ha^{-1} of fertilizer N (Bacon et al., 1989). When 100 kg N ha^{-1} in fertilizer was applied, wheat grown in a Mediterranean climate accumulated 125.5 kg N ha^{-1}, of which 76.4 kg or 61% of the total N in the crop was derived from SOM (Garabet et al., 1998). The importance of SOM as a source of N for crops in temperate and tropical environments was also pointed out earlier (Bigeriego et al., 1979; Sanchez and Jama, 2002; Stevens et al., 2005).

While inorganic fertilizer N provides an immediate source of mineral N for the crop, the majority of the N in the crop is often derived from N that is stored in the SOM. Maintaining SOM levels will therefore remain a crucial component of sustainable agricultural practices (Swift and Woomer, 1993), as will management practices designed to maximize synchronization between the release of N from soil sources and the time of maximum N uptake by crops.

Fertilizer Nitrogen Use Efficiency

The percentage of the total N in the crop derived from ^{15}N fertilizer for the first cropping cycle for the two residue management practices ranged between 7 and 58%. Conversely, between 42 and 93% of the total N in the crop was derived from soil N (Table 3). On average across all locations and for Treatments 1 and 2, 21% of the N in the crop was derived from fertilizer N in the growing season when the ^{15}N-labeled fertilizer was applied, whereas the remaining 79% was derived from the soil-N pool.

The majority of the fertilizer N was not used by the crop during the growing season when it was applied. The average recovery of the applied fertilizer ^{15}N by all crops across all agroecosystems and the two residues management practices was found to be only 33% (overall range 7–63%, with the majority being in the range 25–44%; upper part of Table 3). The low value for N use efficiency (NUE) in Malaysia (20%) was mainly caused by heavy rainfall, which occurred immediately after the application of the ^{15}N fertilizer, whereas the very low NUE value in Chile (7%) was probably caused by high soil mineral N (Table 1). Hence, on average, 67% of the fertilizer N applied was not recovered in the grain plus straw by the different crops during the first growing season. Recoveries of ^{15}N fertilizer by annual crops are highly variable and affected by different management practices and biophysical factors. Although the crop recoveries reported here are lower than many reported from temperate regions, they are not unusual compared with others from warmer climatic zones. For example, under different straw management practices, the average fertilizer-^{15}N use efficiency by flooded rice in experiments in California was 37%, which included the ^{15}N recovered in the grain and residue (Eagle et al., 2001). Depending on the use of P fertilizers, the recovery of ^{15}N-urea in bread wheat in the Ethiopian highlands ranged between 25.3 and 60.4% (Gorfu et al., 2003); large ^{15}N losses were associated with high rainfall in combination with a heavy clay soil and high soil N supply. Crop recoveries of ^{15}N-labeled fertilizer applied to winter wheat in the UK (temperate climate) varied between 56 and 87% across sites and years (Powlson et al., 1992). In another UK study, average ^{15}N-fertilizer recoveries in crops ranged between 45 and 61% for winter wheat, oilseed rape (*Brassica napus* L. var. *napus*), potato (*Solanum tuberosum* L.), and sugarbeet (*Beta vulgaris* L. ssp. *vulgaris*) in a temperate region, whereas spring bean only recovered 26% (Macdonald et al., 1997). In the UK examples, fertilizer N losses were found to be controlled more by weather conditions (higher rainfall following application of the fertilizer) than by cropping history or soil type.

Low FUE is largely caused by three factors: (i) poor synchronization between the availability and amount of fertilizer N applied with the demand for N by the crop, (ii) high losses of fertilizer N due to gaseous N emissions or leaching and runoff, and (iii) high available soil N levels, possibly in combination with high soil N supply power. A fourth cause of lower fertilizer-^{15}N recovery by the crops may be due to methodology: ^{15}N isotope dilution vs. the N-difference method. For the N-difference method, fertilizer-N recovery is calculated by the difference in total crop N of N-fertilized and unfertilized crops. Fertilizer-N recoveries, including both grain and residue, of around 50% based on the N-difference method were found when calculated on a global scale (50%; Smil, 1999), for Canada (56%; Janzen et al., 2003), or the United States (52%; Howarth et al., 2002). When the fertilizer-N recovery is based solely on total N in the grain, the recovery is 30% of the N fertilizer applied (Ladha et al., 2005).

Values of FUE estimated by the ^{15}N isotope method have been reported that are higher than, similar to, or lower than the FUE calculated by the N-difference method (Roberts and Janzen, 1990; Jokela and Randall, 1997; Schindler and Knighton, 1999; Jenkinson et al., 1985). Ladha et al. (2005) calculated that the average recovery of ^{15}N fertilizer in grain of field-grown maize, rice, and wheat increased from 30 to 44% when recovery in the straw was included. This compared with 55% recovery in the grain plus straw using the N-difference method. Lower estimates for FUE by the ^{15}N method compared with the N-difference method are mainly caused by pool substitution, whereby ^{15}N stands proxy for ^{14}N that would otherwise have been immobilized into the microbial biomass (Roberts and Janzen, 1990).

Lower estimates by the ^{15}N method than the N-difference method are also caused by the exclusion of any residual or "memory" effects of ^{15}N fertilizer from previous years, whereas the N-difference method includes the overall effect of ^{14}N fertilizers applied including the effect of previous years' applications. For example, Jenkinson et al. (2004) found that in old grassland the recovery of N applied as NO_3 was 49.8% when based on the ^{15}N-isotope data but increased to 90.7% when based on the N-difference method using long-term plots. If ^{15}N fertilizers were applied repeatedly for many years, the recovery of fertilizer N based on isotope data and the N-difference method would eventually become equal. Therefore, some caution is warranted when discussing FUE and the method used. If the objective is to determine strictly the FUE in a first growing season following the application of fertilizer N, the ^{15}N-isotope method is appropriate. On the other hand, if the objective is the determination of the recovery of fertilizer-N applications, including residual N recovered during subsequent growing seasons, the N-difference method would provide a more realistic estimate of fertilizer-N use by the crop. Of course, ^{15}N labeling is essential for detailed studies of transformations and processes once fertilizer-derived N has entered soil pools.

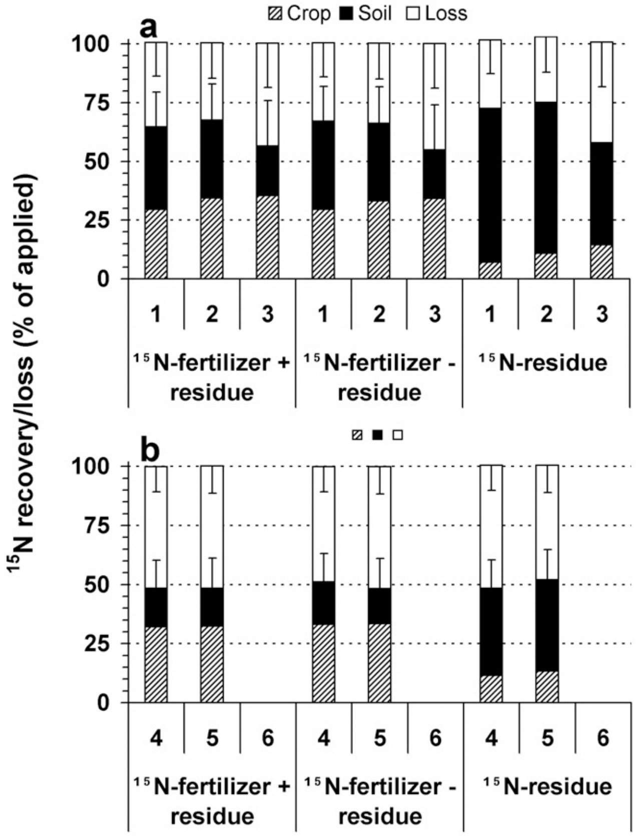

Fig. 1. Mean cumulative crop and soil ^{15}N recovery and ^{15}N losses in (a) the first three growing seasons (1–3) and (b) last three growing seasons (4–6) after the commencement of the experiment. The growing season is indicated in the upper portion of the *x* axis label, with the treatment indicated immediately below. Error bars are LSD(0.05) to compare treatment means. Each growing season and variable (crop, soil, and loss) have a unique LSD(0.05) value.

It is also essential for estimating the total recovery of N in the crop and soil, and hence the quantity of fertilizer N lost.

Residual Fertilizer Nitrogen-15 Uptake by Subsequent Crops

At the end of the growing season, residual N from fertilizer (i.e., ^{15}N fertilizer not removed through the grain and residue or lost from the system) remains in the soil in the following forms: as mineral N, in roots, immobilized into the microbial biomass, or incorporated into other SOM pools (Powlson et al., 1986; Bradbury et al., 1993). In most situations, with reasonable rates of fertilizer N being applied, the amount of ^{15}N in the various organic forms far exceeds the residual ^{15}N in mineral forms. Following net mineralization, organically bound ^{15}N can become available for plant uptake during the subsequent growing seasons. After the first growing season, however, the amount of ^{15}N in the roots generally becomes negligible and the remaining ^{15}N fertilizer would have become part of a more stable SOM pool or lost from the cropping system (Jansson and Persson, 1982). Once these SOM pools undergo net mineralization, these pools become a source of ^{15}N.

To determine the amount of fertilizer-derived N that subsequent crops accumulate, the use of ^{15}N fertilizer is essential. In our study, the average, cumulative N fertilizer used by all crops grown across all regions, soil types, and environmental zones in the second to sixth growing season was 5.3% of the N applied (Fig. 1 and 2), which corresponds to about 16% of the mean FUE found for the first growing season (Table 3). Thus, taking account of this uptake of residual ^{15}N would increase the FUE to 38% compared with the single-season value of 33% (Table 3). As expected, most of the additional fertilizer-N recovery occurred in the second growing season and decreased to 1% or less in subsequent growing seasons (Fig. 1 and 2). Crop recoveries across locations of ^{15}N-labeled fertilizer for the fourth to the sixth growing seasons were small relative to the recoveries observed in the year the ^{15}N-labeled fertilizer was applied (Table 3; Fig. 2). The number of locations where the experiment with ^{15}N fertilizers could be continued for more than three growing seasons decreased from 13 to five when ^{15}N fertilizer was traced and four locations when ^{15}N residue was followed.

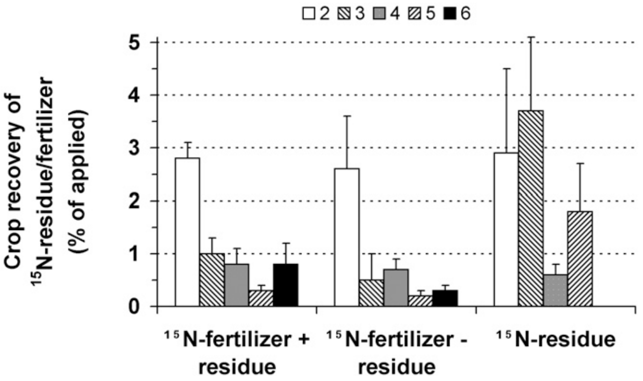

Fig. 2. Average ^{15}N in crop derived from a single application of ^{15}N-labeled fertilizer or ^{15}N-labeled residues in subsequent growing seasons. The legend (2–6) refers to the number of growing seasons after the commencement of the experiment, with 1 being the year the ^{15}N was applied. Error bars are LSD(0.05) to compare treatment means, with each growing season having a unique LSD(0.05).

Although the vast majority of field studies using labeled ^{15}N fertilizer to determine fertilizer N use are limited to the first growing season, there are some in which the uptake of residual fertilizer N during the subsequent growing season(s) has been measured. Recovery of residual fertilizer N from the original application in the subsequent crops is often <5% of the N fertilizer applied and seems to be unrelated to location or the crop grown. For example, millet [*Eleusine coracana* (L.) Gaertn.] in a maize–millet rotation in Nepal recovered 3% of the ^{15}N-urea applied to the previous maize crop (Pilbeam et al., 2002). The recovery of residual ^{15}N-urea–NH_4NO_3 in maize for three subsequent growing seasons in a continuous maize system in the United States ranged between 1.7 and 3.5% (Timmons and Cruse, 1991); the amounts of residual fertilizer N uptake were considered to be too small to be taken into consideration when making fertilizer-N recommendations. Total ^{15}N-urea recovery in the second year in acala cotton (*Gossypium hirsutum* L.) in California averaged 5.8% of the original application and declined to 2.7% in the third year (Fritschi et al., 2005). After the third growing season, on average, 40% of the applied fertilizer was recovered in the soil, mainly in the 0- to 30-cm layer. Kumar and Goh (2002) reported that the average residual recovery by wheat during three subsequent growing seasons after applying

^{15}N-$(NH_4)_2SO_4$ to ryegrass (*Lolium perenne* L.) or wheat was 7.0%. Of this, 3.7% was accumulated during the first subsequent growing season and, on average, 30% of the applied ^{15}N was recovered in the soil. In a study in a humid subtropical environment in Korea, ^{15}N-$(NH_4)_2SO_4$ was applied to maize; only 1.6% of the original ^{15}N application was recovered in the stover and grain of maize grown as the subsequent year's crop (Seo et al., 2006). When ^{15}N-labeled NH_4NO_3 was applied to winter wheat at three sites in the UK (temperate climate), at different rates and in four application years, between 1.1 and 2.5% of the original application of the ^{15}N fertilizer was taken up by the wheat in the year after application; this decreased to between 0.4 and 0.5% in the fourth year (Hart et al., 1993). These amounts were between 4 and 11% of the ^{15}N remaining in the soil after the first harvest. Similarly low values for ^{15}N-fertilizer recovery in the subsequent crop have also been reported for spring wheat (Ladd and Amato, 1986; Janzen et al., 1990). Applying urea for 8 yr failed to show a measurable residual-N effect on rice grain yield and N uptake (Ladha et al., 2005). The absence of a residual fertilizer N effect was also corroborated with insignificant changes in the total soil N content.

In general, it can be concluded that the recovery of ^{15}N fertilizer, based on the original application, by a crop grown in the second or subsequent growing seasons is very small and will not meet, in a significant way, crop demand for N. The importance of residual fertilizer N for agroecosystems, therefore, will not be in the amount of N provided to the subsequent crop but in its role in replenishing soil organic N pools. Glendining and Powlson (1995) reviewed data from numerous long-term studies worldwide and reported that long-continued applications of inorganic N fertilizer increased either total soil N, various organic N fractions, or N mineralization compared with zero-N treatments on a decadal time scale. In our studies, about a third of the ^{15}N fertilizer was recovered in the soil at the end of the first growing season, which decreased to an average of 17% after six growing seasons (Fig. 1). As, on average, 79% of the N in the crop was derived from soil N, the long-lasting residual effect of fertilizer N will be through its presence as organic N in the soil and its subsequent release with time as mineral N.

In our experiments, removing or incorporating residues following the application of ^{15}N fertilizer in the subsequent growing season had no effect on FUE (Fig. 1a) or on the fate of residual ^{15}N in subsequent years (Fig. 1a and 1b). If residue management is to be used as a management practice to improve fertilizer N use efficiency, application would have to take place prior to or at the time of applying fertilizer N.

Residue Nitrogen-15 Uptake by Subsequent Crops

Crop residues serve as a source of mineral N for the crop and, through the buildup of SOM, improve the soil quality and C and N content (Ladd et al., 1981; Janzen et al., 1990). The amount of N from residues taken up by the subsequent crop is highly variable and dependent on the physical and chemical characteristics of the residue in addition to the soil type and environmental factors such as temperature and soil moisture (Fox et al., 1990; Vanlauwe et al., 1996). The proportion of the plant-available residue N actually accumulated by the crop is also dependent on how well the release of N from the residue is synchronized with the N demand of the crop (Giller and Cadish, 1995). Excellent synchronization between the rate of net N mineralization of residue N and the demand for N by the crop is desirable, as it will reduce the likelihood of N being lost through denitrification, leaching, or other mechanisms of mineral N loss. In fact, such close synchronization is hard to achieve in many environments.

In our experiments, the percentage of N in the subsequent crop derived from residue ^{15}N ranged between <1% (wheat and maize in Chile, wheat in Egypt) to 11.7% (rice in China) (Table 3). On average, only 3.9% of the total N in the subsequent crop was derived from ^{15}N-labeled residues. It should be noted that the quantity of N derived from the soil cannot be determined in the experiments with ^{15}N-labeled residues because unlabeled N fertilizer was applied in all years to make the growing conditions of the crop as normal as possible. Thus crop uptake of unlabeled N was derived from a combination of N mineralized from the soil plus the unlabeled fertilizer.

The NUE from residue N by the subsequent crop averaged 7%, with <1% in several cases to a maximum recovery of 30.9% of sunflower residue N by wheat in Morocco (Table 3). In all instances, the majority of the ^{15}N recovery, excluding the first growing season, occurred in the second and third growing seasons, with small (<1%) recoveries of fertilizer N per growing season after the third (Fig. 2).

The large range in values in residue-^{15}N recovery observed here is probably caused by multiple factors. The particularly low recovery of residue ^{15}N by crops in Chile (Table 3; also the low FUE of fertilizer N by wheat at this site) was probably due to the high content of plant-available N and mineral N in the soil at this site (Table 1). Differences in residue quality (Table 2) affect the rate of net N release, which affects the degree of synchronization of net N mineralized with crop N demand (Myers et al., 1994). Rates of N mineralization, in turn, are influenced by climatic conditions, like temperature and soil moisture content (Bradbury et al., 1993). Recoveries of residue ^{15}N by the subsequent crops have been reported to vary widely. A distinction, however, should be made between recoveries of N by the subsequent crop from (i) residues that remain in the field following the harvest of the grain, and (ii) residue crops that are grown specifically to increase N in the system through biological N_2 fixation or serve as a catch crop of mineral N, which is prone to leaching during a fallow period. In general, significantly higher recoveries of residue N from cover or green manure crops are found than from residues of crops that have been harvested for grain. Using lentil (*Lens culinaris* Medik. ssp. *culinaris*) as a green manure crop, 19% of its N was accumulated by the subsequent wheat crop, whereas when lentil was harvested for grain followed by incorporation of its residue, only 5.5% of its N was accumulated by wheat (Bremer and van Kessel, 1992). In the United States, the recovery of ^{15}N-labeled spring wheat residue by the subsequent winter wheat crop was 9% (Fredrickson et al., 1982). In a comprehensive study conducted in New Zealand on the multiyear recovery of ^{15}N-labeled residues, the first wheat crop recovered 11 and 13% of the residue ^{15}N of ryegrass (*Lolium perenne* L.) and wheat, respectively (Kumar et al., 2001). When wheat was grown in rotation with white clover (*Trifolium repens* L.) and field pea (*Pisum sativum* L.), however, recoveries of 29 and 37% were obtained for field pea and white clover residue N, respectively. In general, more organic N is applied when legume residues are used and their C/N ratios are more narrow, leading to higher rates of net N mineralization.

In the current study, the cumulative uptake of residue ^{15}N by crops grown from the second to the sixth growing seasons was 6.1% of the applied residue N, which was slightly higher than the average cumulative uptake of fertilizer ^{15}N during this period, i.e., 4.8%. On average, across these five growing seasons and all sites, the recovery was slightly more than 1% per growing season of the residue N applied. Although an annual contribution of 1% of residue N supplied to the crop has no practical significance when making fertilizer-N recommendations, the contribution reflects the long-term role of SOM in supplying N to the crop.

Information on the recoveries of residue ^{15}N by crops after the first year of application remains scarce as the majority of studies are limited to measuring the recovery of residue N by the first crop following residue application. When the residual contribution of white clover and pea residue and root N plus fertilizer N was followed, between 5 and 8% of the N was recovered by wheat in the second and third subsequent crops (Kumar et al., 2001). When wheat was grown in the second and third years after the incorporation of ryegrass and winter wheat residue, wheat recovered between 2 and 4% of the N. When ^{15}N-labeled *Medicago littoralis* (Rohde ex Loisel.) with a C/N ratio of 11.1 was applied, the second wheat crop accumulated 4.2% of the ^{15}N input (Ladd and Amato, 1986). Based on the results of this and other studies, these researchers concluded that for legume residues with low C/N ratios (11.1–14.9) and decomposing in sandy loam topsoil, every 10 kg of N applied as legume residue contributed 2% of the N of the first subsequent crop and 1% of the N of the second crop. Although the C/N ratio of the residues will have an effect on the availability and uptake of N by the first subsequent crop, its effect on the recovery of ^{15}N by following crops may be limited. Most of the residue will have undergone biological transformations within the first year following application, with the remaining residue incorporated into the SOM (Ladd and Amato, 1986).

Total Nitrogen-15 Recovery in Plant and Soil

Most the total ^{15}N losses from either fertilizers or residues occurred in the year of application. Averaged across our studies at 13 sites worldwide, about one-third of the N applied as ^{15}N fertilizer and 25% of that applied as ^{15}N residue was lost during the first growing season (Fig. 1a). A wide range of losses of ^{15}N during the first growing season has been reported. Total ^{15}N losses of N contained in hairy vetch (*Vicia villosa* Roth) were between 41 and 46% during the first growing season, whereas losses of fertilizer N were between 38 and 53% in a subtropical climate in Korea (Seo et al., 2006). Depending on the quality of the residue, and excluding burning the residue, between 15 and 70% of the ^{15}N applied as residue was not recovered in a wheat crop or in the 0- to 40-cm soil depth (Kumar et al., 2001). In California, Kramer et al. (2002) found that average ^{15}N losses were 33% after the first growing season and were independent of whether N was applied in organic or inorganic forms, and also independent of cropping system, i.e., conventional, organic, or a low-input systems. Harris et al. (1994) followed the fate of fertilizer and clover N in conventional and organic systems and after 2 yr, 43% of the fertilizer N and 35% of the clover N was lost. When wheat and sorghum residues were applied, however, the total recovery was close to 100%, with between 81 and 95% of the N recovered in the soil (Wagger et al., 1985). It is probable that immobilization of ^{15}N fertilizer occurred when wheat and sorghum residues were applied, thereby reducing N losses. In our work after five (residue) and six (fertilizer) growing seasons, on average 54% of the ^{15}N was accounted for in the crop and soil, with similar recoveries for ^{15}N fertilizer (53%) and ^{15}N residue (55%) (Fig. 1b). Based on these findings, it can be concluded that, from the viewpoint of retaining N within the agroecosystem (i.e., N retention in crop and soil), fertilizer N and organic N from crop residues are similar. The total amount of ^{15}N retained will depend on a number of factors such as soil type and N supplying power, residue quality and management, climatic conditions, and fertilizer-N management practices such as rate, timing, and placement (Kumar and Goh, 2001).

The main difference in total recovery between fertilizer N and organic N is the distribution between crop and soil. On average, the total recovery of ^{15}N from fertilizer N in the crop and soil after six growing seasons was 53% of the applied N. When applied as ^{15}N residue, the total recovery in the crop and soil was 55% (Fig. 1b). Thus, the percentage of the ^{15}N recovered in the crop and soil after five (^{15}N residue) or six (^{15}N fertilizer) growing seasons was independent whether applied as fertilizer or residue: the mean across all treatments and sites was 54%. When the ^{15}N was applied as fertilizer, however, approximately two-thirds of that in the crop and soil was recovered in the crop and the remaining one-third in the soil. In contrast, when the N was applied as ^{15}N residue, the average recovery in the crop (based on the fourth and fifth growing seasons) was 25%, with the remaining 75% recovered in the soil. A similar pattern of recovery of ^{15}N in the plant vs. the soil when fertilizer and residue N was applied occurred in a comparison of conventional and low-input systems (Harris et al., 1994).

Our results, from a diverse range of tropical agroecosystems, show that fertilizer N served as an available source of N for the crop but contributed less to the replenishment of N in the SOM. The opposite occurred for residue N, which only provided limited amounts of N to the crop but contributed much more to sustaining and building up the N reserve in the SOM. Because on average 79% of the N in the crop was obtained from soil organic N, maintaining the SOM content remains crucial, and crop residues will play an important role. As an adequate supply of mineral N is required to sustain crop growth and yield, fertilizer N will be a main source to provide this N. Therefore, for tropical agroecosystems, management practices to enhance crop yield and sustain soil fertility should focus on how to improve the use of both inorganic and organic sources of N. One possible management practice is the combined application of organic and inorganic sources of N. Beneficial interactions when fertilizer and residue inputs of different qualities are combined have been proposed (Vanlauwe et al., 2001). Possible temporary immobilization of fertilizer N, which is subsequently released following net N mineralization, might improve the synchrony of N being released and uptake of N by the crop.

Environmental Factors Controlling Total Nitrogen-15 Recovery in Plant and Soil

Site was the dominant single factor influencing the recovery of ^{15}N in the crop and soil, whereas growing season or the form of applied ^{15}N (synthetic fertilizer or crop residue) was less important (Table 5). Regarding the various site factors, soil texture, pH, available P and K, and bulk density had little effect on the total ^{15}N recovery. Overall, covariance analysis showed that, at the end of the third growing season, annual rainfall and mean annual temperature had the largest effects on ^{15}N recoveries, in particular when the ^{15}N was applied as residue N (Fig. 3). Increasing the annual rainfall or temperature between sites led to a marked and highly significant decrease in the recovery of ^{15}N residue in the crop and soil. This was mainly a result of decreased recovery of residue N in the soil, as the influence of rainfall and temperature on recovery in the crop was much less strong (Fig. 3).

Berntsen et al. (2007) found that the SOM content had little effect on the ^{15}N recovery of manure-derived N in the soil. Therefore climate, as characterized by rainfall and mean annual temperature, became the most dominant factors influencing ^{15}N losses: overall, higher temperature and higher rainfall led to higher total ^{15}N losses, i.e., lower recoveries in the crop and soil (Fig. 3). In particular for ^{15}N residue, its total recovery (crop and soil) was significantly dependent on mean annual temperature, with higher temperature leading to higher ^{15}N losses. High mean temperature and rainfall will increase the rate of decomposition of residue. If the release of mineral N from residues is not well synchronized with crop N uptake, the increase in net N mineralization will lead to higher leaching and denitrification losses under high rainfall. Although mean annual temperature and annual rainfall had no significant effect on the recovery of ^{15}N fertilizer, there was an overall tendency of lower recovery of ^{15}N in the crop and soil with higher annual rainfall and temperature (Fig. 3). High rainfall and mean annual temperature tends to promote lower ^{15}N recoveries in the crop and lower total recoveries in plant and soil. In temperate region studies, higher rainfall in a 3-wk period following ^{15}N-fertilizer application led to significantly higher losses in the UK (Powlson et al., 1992; Macdonald et al., 1997). Pilbeam (1996), however, reviewing results from a range of mainly tropical sites, found that an increase in rainfall increased crop ^{15}N uptake, decreased ^{15}N recovery in the soil, and had no effect on total ^{15}N recovery in the crop and soil. Most of the studies evaluated by Pilbeam (1996) were located in dryland areas with much lower rainfall than found in our study (Table 2). At these low-rainfall sites, crop growth was constrained by a lack of water, so higher rainfall promoted crop growth and generally decreased the risk of N loss by increasing the role of the crop as an N sink.

Somewhat surprisingly, there was a higher average recovery of ^{15}N fertilizer in the soil in the tropical environments of this study than in earlier studies in temperate regions (see Fig. 1; Powlson et al., 1992; Glendining et al., 1997; Macdonald et al., 1997). The mean average recovery of ^{15}N fertilizer in the crop after the first growing season was 33%, with 37% remaining in the soil. In a temperate climate, the mean average recovery of ^{15}N fertilizer after the first growing season was 56% in the crop and 25% remaining in the soil, averaged across five soil types and five arable crops repeated for five seasons (Powlson et al., 1992; Glendining et al., 1997; Macdonald et al., 1997). One possible explanation may be that immobilization of N fertilizer is more dominant or rapid in a tropical environment, and once fertilizer N is immobilized it is less subject to loss.

Table 5. Analysis of variance results for crop and soil ^{15}N recovery data collected during the first three (13 locations) and the last three growing seasons (four to seven locations).

Time period and effect	Crop	Soil	Crop + soil	Loss
First three growing seasons				
		P value		
Treatment (T)	<0.001	0.007	0.903	0.855
Growing season (G)	<0.001	<0.001	<0.001	<0.001
G × T	<0.001	0.588	0.821	0.837
	Variance estimate, (% N recovery or loss)^2			
Site (S)	56.9*	86	325*	347*
S × T	23.9**	474**	417**	424**
		Total variance, %†		
S	70	15	44	45
S × T	30	85	56	55
Last three growing seasons				
		P value		
T	<0.001	0.053	0.800	0.666
G	<0.001	0.005	0.016	0.014
G × T	0.001	0.016	0.006	0.009
	Variance estimate, (% N recovery or loss)^2			
S	155*	277	736*	747*
S × T	21**	136**	81*	75*
		Total variance, %†		
S	88	67	90	91
S × T	12	33	10	9

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

† The variance for a given effect, divided by the sum of the variance estimate for the four effects associated with the site, multiplied by 100.

For the sites in this study, recovery of ^{15}N residue in the crop and soil significantly increased with an increase in cation exchange capacity and soil organic C content (Fig. 3). The cation exchange capacity is related to both clay and soil organic C content (Brady and Weil, 1996). It seems probable that the increasing recovery in the crop and soil of ^{15}N residues with increasing cation exchange capacity (Fig. 3) reflects greater stabilization (i.e., slower decomposition) of organic residues in soils of higher clay content. This influence would also tend to increase the stability (i.e., decrease the rate of remineralization) of ^{15}N derived from fertilizer after its initial immobilization in the soil during the season of application. As soil organic C content tends to be higher in soils of higher clay content, increased recovery of ^{15}N residue would also be expected as soil organic C increases across the sites, as also seen in Fig. 3. Numerous other controls and unidentified interactions

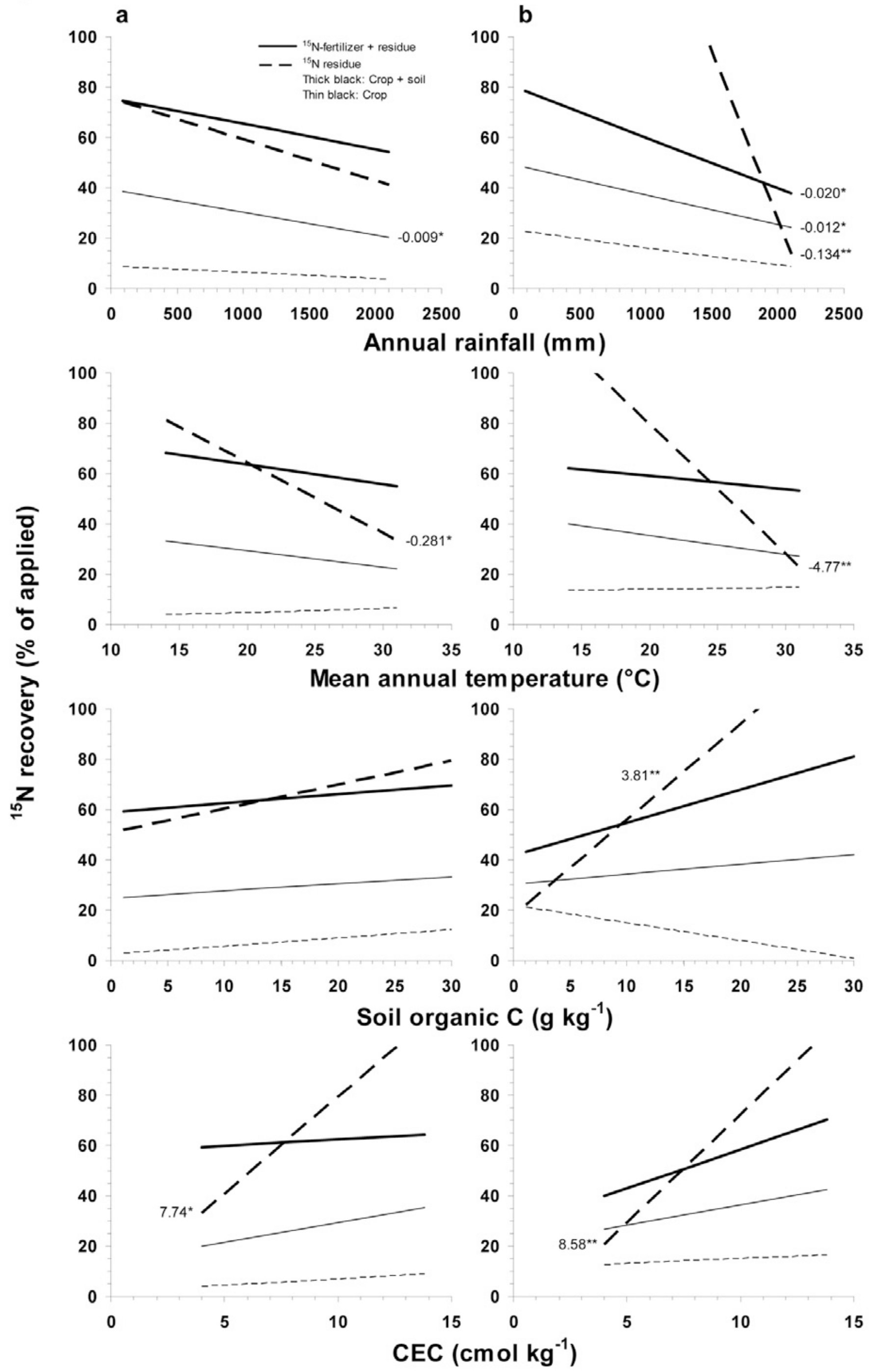

Fig. 3. Crop and crop + soil ^{15}N recovery responses to climate and soil-related covariables across the 13 locations for two management treatments during (a) the first and (b) the third growing seasons; CEC is cation exchange capacity. Responses for the ^{15}N-labeled fertilizer minus residue treatment were similar to those for the ^{15}N-labeled fertilizer plus residue treatment and thus are not shown. The slope coefficients for significant ^{15}N recovery responses relative to the covariables are shown, and their statistical significance is displayed: * $P < 0.05$; ** $P < 0.01$.

between factors are likely to have contributed to the actual losses or retention of ^{15}N at the individual sites.

CONCLUSIONS

Despite the vital role of fertilizer N in increasing crop yield and achieving food security, SOM emerged as the main source of N for crop production across tropical agroecosystems in this study. On average, 79% of the N in the N-fertilized crop was derived from SOM in the experiments reported here from 13 mainly tropical sites. Although, on average, only one-third of the fertilizer N was recovered by the crop in the year of N-fertilizer application, a further one-third of the fertilizer N became part of the SOM, sustaining the role of SOM in providing N to subsequent crops.

Although residue N was a poor supplier of N to the crop in the first growing season, its contribution to SOM maintenance was about double that of fertilizer N. Therefore, the long-term effect of crop residues on providing mineral N to the crop will be greater than that of fertilizer N.

In this study, climatic conditions, i.e., rainfall and temperature, rather than soil characteristics, were the dominant factors influencing ^{15}N losses: higher mean annual temperature and rainfall generally led to higher losses, in particular for residue ^{15}N (Fig. 3). Therefore, losses of fertilizer and residue N in the humid tropics are likely to be more pronounced than in temperate or semiarid regions. Despite the general dominance of climatic factors in influencing N losses, for ^{15}N applied as organic residue there was also a trend for lower losses across several growing seasons in soils with higher cation exchange capacity (Fig. 3); this presumably reflects greater stabilization of N in organic forms in such soils, leading to lower rates of mineralization.

Total recoveries of ^{15}N in plant and soil after six growing seasons, averaged across four to six locations, were 54% and independent of whether N was applied as synthetic ^{15}N fertilizer or as ^{15}N residue (Fig. 1). The recovery of applied N found in our study is remarkably similar to the value reported by Smil (1999), who calculated, using the N balance method, that 50% of fertilizer N is lost. On a global scale, this implies that of the 100 million Mg of fertilizer N applied to crops annually, approximately 50 million Mg is unaccounted for in soil or crop. Sixty percent of the total losses of fertilizer N occur during the first growing season. Thus there remains considerable potential to improve FUE and reduce N losses, thereby reducing the environmental burden of lost N and increasing the economic performance of tropical cropping systems. The inability to control rainfall and temperature, however, will make it a considerable challenge to significantly reduce N losses in humid, tropical environments. This highlights the urgent need for agronomic research in such regions to develop management practices to control N losses.

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