A SIMPLE MODEL TO DEFINE THE QUANTITY AND THE DYNAMICS OF NITROGEN APPLICATION BASED ON ORGANIC MATTER TURNOVER USING NUCLEAR TECHNIQUES

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Abstract

This study is related to the IAEA/FAO Co-ordinated Research Project (CRP) No. DI-40.08, "The use of isotope techniques in studies on the management of organic matter and nutrient turnover for increased, sustainable agricultural production and environmental preservation," concerned with the use of isotope techniques for studying ways of improving management of organic matter and nutrients in soil as a contribution to sustainable agricultural production and environmental preservation. The fate of N from two different sources (inorganic fertilizer or crop residues) was followed after a single pulse of ^{15}N-labelled material (fertilizer or residues) at thirteen sites in several developing countries covering a wide range of climates, soils, and crop rotations. Nitrogen added to the soil via ^{15}N-labelled fertilizer (ammonium sulphate) ranged from 35 to 300 kg N/ha, and via ^{15}N-labelled crop residues ranged from 12 to 160 kg N/ha. The fate of the residual ^{15}N in soil, both in the presence and in the absence of crop residues, was also followed, according to the following treatments. T1: ^{15}N-labelled fertilizer and unlabelled crop residues added, T2: unlabelled fertilizer and ^{15}N-labelled crop residues added, and T4: ^{15}N-labelled fertilizer added without crop residues. A simple descriptive mathematical model was developed to synthesize information collected at all experimental sites, allowing comparisons between treatments and sites. The descriptive model generated curves representing the fate of fertilizer N in the soil, crop, and crop-soil compartments. The generated curves showed similar patterns for all cases studied: major losses of the fertilizer N occurred during the first cropping season, and then only small losses occurred in the following cropping seasons. Nitrogen retention in the crop-soil system ranged from 13 to 66% of the fertilizer N applied, with no significant impacts of crop-residue management (losses varied between 45 and 85% of the fertilizer N applied), and from 1 to 37% of the N applied via crop residues. When N was applied via crop residues, retention in soil was much greater than when N was applied via inorganic fertilizers, but the recovery in the crop-soil system was poor due to very low uptake rate by the crop, probably because of lack of synchrony between N release from the residues and N demand by the crop. The proposed model described well the fate of fertilizer N in all compartments, generating curves that allow easy visualization in every case studied. Thus, the descriptive model proposed in this study proved to be an efficient tool for making comparisons between treatments and between sites.

1. INTRODUCTION

In the second half of the twentieth century, inorganic fertilizers largely replaced organic amendments, both in developed and developing countries, but there is now renewed interest in the application of organic residues to the soil as a means of improving its quality and thus sustaining its fertility and productiveness.

Soils in many developing countries have low inherent fertility, are old and highly weathered, and have lost their capacity to retain and exchange nutrients.

Furthermore, more importantly than focusing only on nutrient additions, one should be aware that nutrient losses must be drastically reduced. In the case of nitrogen (N), the main object of this study, losses can occur through leaching, gaseous conversions, and run-off.

The organic matter present in soil (SOM) strongly influences several properties. It is well known that it enhances soil structure and stability, thus improving root development (reducing soil density and increasing aeration and water-holding capacity), and minimizing risks of erosion. The presence of organic matter is also essential for a soil to be able to capture (e.g. N_2 fixation by soil micro-organisms), store and recycle nutrients.

Soil organic matter serves as a temporary storage place of energy and nutrients. When soil micro-organisms use the stored energy, nutrients may be released and become available for plant uptake. Therefore, one of the most important factors to be dealt with is synchrony of nutrient release by different SOM pools and nutrient demand by the crop.

The objective of this study was to understand the N dynamics after a single input of the nutrient into the soil (via fertilizer or via crop residues) and how soil-N dynamics are affected by adding carbon (C) to the soil, in the form of crop residues.

A simple simulation model was developed in order to synthesize information collected in nine developing countries (Bangladesh, Brazil, Chile, China, Egypt, Malaysia, Morocco, Sri Lanka, and Viet Nam), covering a wide range of soils (Oxisols to Vertisols) and climatic regions (semi-arid to humid tropics). This activity is a first step in improving our understanding of N dynamics under various residue-management practices with the aim of identifying strategies and new management practices that will increase N use efficiency.

2. MATERIALS AND METHODS

2.1. SOM dynamics and models

A comprehensive list of SOM models was retrieved from the Global Change and Terrestrial Ecosystems–Soil Organic Matter Network (GCTE-SOMNET at http://www.res.bbsrc.ac.uk/soils/somnet). Based on model characteristics described in the GCTE-SOMNET list and in a review [1], seven were chosen and studied:

— CANDY
— CENTURY
— DAISY
— DNDC
— NCSOIL
— RothC
— Verbenne

The main objective of these models is the simulation of long-term changes in SOM content. Even though measurable changes in SOM content may occur within 5 years or less in tropical regions, longer-term studies would be preferable to better access these changes. Since it was not possible to undertake long-term studies within the scope of the CRP, efforts were directed towards studying N dynamics in the short term.

2.2. Short-term N dynamics

Fertilizer N applied to a crop may follow several paths. It may be taken up by the crop and subsequently removed in the harvested part, or returned to the soil in crop residues. Another possibility is that it may be lost from the crop-soil system by a variety of processes, including nitrate leaching, denitrification, and ammonia volatilization. The applied N may also be retained in soil in plant roots or through immobilization into the soil microbial biomass and subsequent transformations into other organic forms.

In order to assess whether the addition of crop residues to the soil enhances the retention and use-efficiency of fertilizer N applied to an area, experiments were carried out in nine developing countries (Bangladesh, Brazil, Chile, China, Egypt, Malaysia, Mexico, Morocco, Sri Lanka, and Viet Nam), using various crop rotations.

These experimental areas covered a wide range of soils (Oxisols to Vertisols), climatic regions (semi-arid to humid tropics), and crop species.

The fate of N from two different sources (inorganic fertilizer or crop residues) was followed after a single pulse of ^{15}N-labelled material (fertilizer or residues). Nitrogen added to the soil via ^{15}N-labelled fertilizer (ammonium sulphate) ranged from 35 to 300 kg N/ha, and via ^{15}N-labelled crop residues ranged from 12 to 160 kg N/ha.

The fate of the residual ^{15}N in soil, both in the presence and in the absence of crop residues, was also followed, according to the following treatments:

T1: ^{15}N-labelled fertilizer and unlabelled crop residues added
T2: unlabelled fertilizer and ^{15}N-labelled crop residues added
T4: ^{15}N-labelled fertilizer added (no crop residues)

Case	Country	Crop rotation
BGD	Bangladesh	wheat–rice
BRA	Brazil	sugarcane
CHIma	Chile	maize–wheat–common bean–barley (maize–wheat–red clover–red clover for T2)
CHIwh	Chile	wheat–common bean–barley (maize–wheat–red clover for T2 and T4)
CPR	China	rice–wheat
EGY	Egypt	groundnut–wheat
MAL	Malaysia	maize–groundnut
MORfw	Morocco	faba bean–wheat
MORsw	Morocco	sunflower–wheat
MORww	Morocco	wheat monoculture
SRLa	Sri Lanka	mung bean–maize (starting in the dry season)
SRLb	Sri Lanka	mung bean–maize (starting in the wet season)
VIE	Viet Nam	maize–soybean

Two main benefits of using ^{15}N-labelled material can be mentioned: the total recovery of applied N in the crop-soil system can be measured, thus providing information on losses, and the location, forms, and subsequent fate of the N retained in the soil can be studied. This information is essential to analyse N turnover within a cropping system and to devise management practices to increase N use efficiency.

Several different impacts of adding organic C to the soil on the short-term dynamics of added N are possible and will be discussed. Retention of applied N in the crop-soil system, and its uptake by crops, can be either increased or decreased by the addition of crop residues, depending on immobilization and remineralization rates at the site.

To organize information and understanding the results obtained, some questions were addressed:

(a) How did the addition of crop residues affect N retention in soil, N losses, and N uptake by the crop, and how is the ^{15}N retained in soil released, taken up by the crop, lost, or recycled during subsequent years in the presence and in the absence of crop residues?

These questions may be answered by comparing treatments T1 and T4 after the first harvest and in the following cropping seasons, since there was a single ^{15}N addition to the first crop.

The addition of crop residues may affect the short-term fate of N added via fertilizers. Possible consequences of the addition of crop residues to the soil are:

— increased retention of the nutrient in the soil (because of increased N immobilization into various SOM pools as a result of increased microbiological activity);
— increased or decreased N uptake by the crop, depending on rates of immobilization and remineralization (N may be rapidly immobilized and then released by remineralization processes), and the synchrony between N mineralization and N demand by the crop;
— decreased losses of N through nitrate leaching, due to increased retention in soil, or increased losses of N, either because C inputs via crop residues may favour denitrification processes or alteration in soil aeration and other physical characteristics may favour ammonia volatilization.

(b) How is the N contained in crop residues released and subsequently retained in soil, lost, or taken up by the crop?

These questions can be answered by analysing treatment T2 over a period of years. Soil organisms decompose crop residues, and nutrients present in the residues may be released and be available to the crop. Several factors affect the turnover processes involved, such as residue quality (content of lignin, content of soluble materials), the population of decomposers and the species present in the site, weather and soil attributes, stochastic events (dry/wet cycles), and contact with soil (affected by tillage management and incorporation of crop residues).

2.3. Modelling N short-term dynamics

A simple mathematical model, descriptive in nature, was developed to synthesize information collected at all of the experimental sites, allowing comparisons between treatments and sites.

The comparison of results between sites is valuable in giving additional insights and a better scientific understanding of processes related to N turnover.

Since the amount of N added, either via inorganic fertilizers or via crop residues, varies within a large range when all experimental sites are considered, relative values of recovery of N by the crop, by the soil, and by the crop-soil system were calculated, according to Eqq. 1, 2, and 3.

$$N_{k,j,s} = \frac{ANE_{k,j}}{ANE_s} \times \frac{QN_{k,j}}{QNA_s} \times 100 \tag{1}$$

where

$N_{k,j,s}$ are amounts of N retained by the soil (compartment 1: k=1) or recovered by the crop (compartment 2: k=2) (kg/100 kg), at the end of the crop cycle j (j=1, 2, 3, ..., n), after a single addition of N to the soil via source s (s=1: fertilizer, or s=2: crop residues),
$ANE_{k,j}$ is the atom % ^{15}N excess in the compartment k (k=1 or k=2), at the end of the crop cycle j (kg/100 kg),
ANE_s is the atom % ^{15}N excess in source s (kg/100 kg),
$QN_{k,j}$ is the quantity of N in the compartment k (k=1 or k=2) (kg/ha), at the end of the crop cycle j,
QNA_s is the quantity of N applied via source s (kg/ha),

K is the compartment: soil (k=1), crop (k=2), or soil plus crop (k=3); in the calculations, each compartment was divided into sub-compartments (soil: 0–15-cm soil layer; 15–30-cm soil layer; 30–50-cm soil layer; crop: plant parts, such as grain, stubble, etc.),

S is the source of N: inorganic fertilizer (s=1) or crop residues (s=2).

$$Nc_{2,j} = \sum_{i=1}^{j} N_{2,i} \quad (2)$$

where

$Nc_{2,j}$ is the cumulative amount of N taken up by the crop (k=2) from cycle i to j (kg/100 kg applied).

$$N_{3,j} = N_{1,j} + Nc_{2,j} \quad (3)$$

where

$N_{3,j}$ is relative N recovery in the crop-soil system (k=3) (kg/100 kg applied), from crop cycle i to j.

Relative N losses in the crop-soil system can be calculated by the difference with relative N recovery in the crop-soil system, according to equation 4.

$$Nl_{3,j} = 100 - N_{3,j} \quad (4)$$

where

$Nl_{3,j}$ is relative N losses in the crop-soil system (k=3) (kg/100 kg applied), from crop cycle i to j.

A conceptual model was developed, based on previous knowledge of N dynamics following a single input of the nutrient, and also on graphical and visual analyses of the temporal variation of $N_{k,j,s}$, and some hypotheses were posed:

Case	Restriction	Consequence	Comments[a]
1	j=0	$N_{k,0}=100$	$N_{1,0}=100$ and $N_{3,0}=100$
2	j→∞	$\lim_{j\to\infty} N_{k,j} = A_k$	$N_{1,j}= A_1= 0$ and $N_{3,j}= A_3=Nc_{2,j}$
3	j=T	$\frac{d^2 N_{k,j}}{dj^2} = 0$	maximum rate of loss (inflection point)
4	0<j<T	$\frac{dN_{k,j}}{dj} < 0$	increasing loss rates
5	j>T	$\frac{dN_{k,j}}{dj} > 0$	decreasing loss rates
6	j=0	$\frac{dN_{k,j}}{dj} = 0$	no losses yet
7	j→∞	$\lim_{j\to\infty} \frac{dN_{k,j}}{dj} = 0$	no extra losses

[a]k=1 or 3 for all cases.

The following equation was designed to represent the temporal variation of relative N retention in the soil and relative N retention in the crop-soil system, based on its ability to fit the experimental data and satisfy the hypotheses above (see Fig. 1):

$$N_{k,j,s} = A_k + \frac{100 - A_k}{1 + B_k . j^{C_k}} \tag{5}$$

where

$N_{k,j,s}$ is $N_{1,j,s}$ (relative N retention in the soil, kg/100 kg applied) or $N_{3,j,s}$ (relative N retention in the crop-soil system, kg/100 kg applied),

A_k, B_k, and C_k are curve-fitting parameters for compartment k (k=1: soil, or k=3: soil-crop system),

A_k, B_k, and C_k integrate the effects of all environmental attributes that may play a role in the N dynamics in the compartment k, following a single addition of the nutrient to the soil, such as rainfall, soil temperature, soil moisture, and soil organisms (species and populations).

These parameters also reflect the effects of added crop residues (taking into account quality of the residues, contact with soil, etc). Thus, Eq. 5 cannot be extrapolated to different scenarios, but is valid only for descriptive purposes.

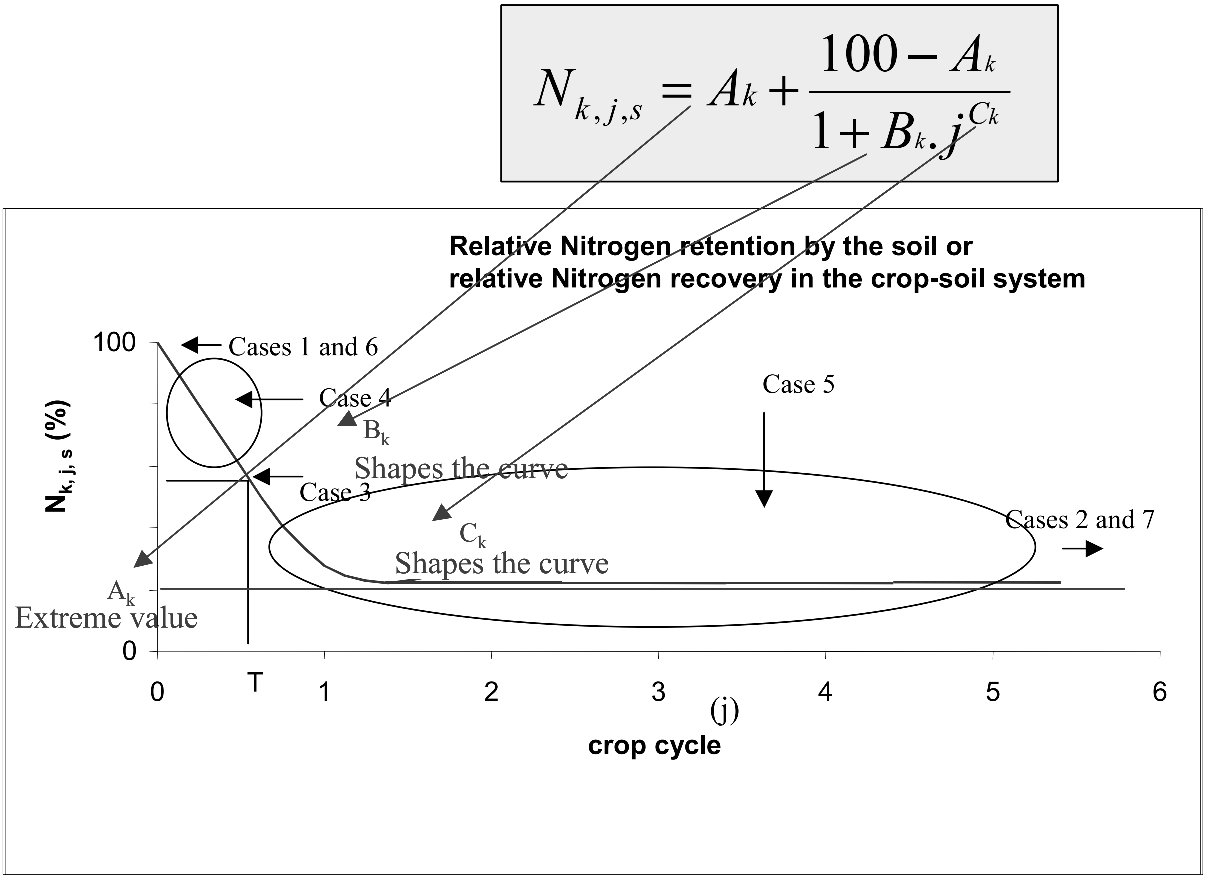

FIG. 1. Performance of Eq. 5, designed to represent the temporal variation of relative N retention in the soil and relative N retention in the crop-soil system; Eq. 5 satisfies all hypotheses (cases 1 to 7).

The proposed simple model consists of the following set of equations:

Calculated values	Estimated values
$\mathrm{N_{k,j,s}} = \frac{\mathrm{ANE_{k,j}}}{\mathrm{ANE_s}} \times \frac{\mathrm{QN_{k,j}}}{\mathrm{QNA_s}} \times 100$ (calculated for k=1 and k=2)	$\hat{N}_{3,j} = A_3 + \frac{100 - A_3}{1 + B_3 \cdot j^{C_3}}$
$Nc_{2,j} = \sum_{i=1}^{j} N_{2,i}$	$\hat{N}_{1,j} = A_1 + \frac{100 - A_1}{1 + B_1 \cdot j^{C_1}}$
$N_{3,j} = N_{1,j} + Nc_{2,j}$	$\hat{Nc}_{2,j} = \hat{N}_{3,j} - \hat{N}_{1,j}$
$Nl_{3,j} = 100 - N_{3,j}$	$\hat{N}_{2,j+1} = \hat{Nc}_{2,j+1} - \hat{Nc}_{2,j}$

Values were calculated for four replicates of the thirteen data sets studied and the model was subsequently fitted to relative N recovery in the crop-soil system ($N_{3,j}$) and N relative retention in soil ($N_{1,j}$), by the least sum of square errors method. Curve-fitting parameters and graphs displaying the fertilizer-N fate in all cases are presented in the Results and Discussion section.

3. RESULTS AND DISCUSSION

3.1 Curve-fitting parameters

The parameters that yielded the best fit for the $N_{3,j}$ (relative N retention in the crop-soil system by the end of cropping season j) curves are listed below:

Case	T1				T2				T4			
	A_3	B_3	C_3	r^2	A_3	B_3	C_3	r^2	A_3	B_3	C_3	r^2
BGD	54.49	0.60	0.12	0.08	30.59	6E–6	5.99	0.18	66.39	3E–4	3.94	0.20
BRA	27.62	4.84	0.01	0.93	5.67	1.89	0.39	0.89	27.39	4.78	0.01	0.77
CHIma	25.16	0.28	2.62	0.80	–	–	–	–	22.53	0.11	3.51	0.76
CHIwh	49.06	0.24	2.38	0.63	1.94	0.16	0.01	0.00	37.79	0.37	2.38	0.48
CPR	34.44	1.33	0.01	0.45	10.06	0.14	0.12	0.03	38.49	1.50	0.01	0.27
EGY	34.06	2.88	0.32	0.77	21.44	0.91	0.74	0.51	33.12	2.70	0.90	0.81
MAL	34.43	0.96	0.43	0.55	9.12	0.68	0.01	0.16	27.97	1.61	0.01	0.41
MORfw	45.00	0.46	0.01	0.31	6.73	1.17	0.39	0.92	45.83	0.57	0.01	0.43
MORsw	37.40	0.53	0.01	0.49	13.69	0.83	0.01	0.87	32.15	0.42	0.17	0.46
MORww	47.01	1.99	0.01	0.44	18.89	0.29	1.77	0.66	40.64	2.54	0.01	0.54
SRLa	14.72	1.26	1.19	0.93	1.64	4.02	0.70	0.98	13.33	0.43	1.80	0.86
SRLb	16.87	0.96	1.29	0.93	0.76	7.87	1.35	1.00	23.72	0.89	1.65	0.95
VIE	48.54	2.24	0.01	0.48	37.20	0.36	0.01	0.11	43.39	1.15	0.47	0.41

A_3 values represent the extreme values of the modelled curves, therefore A_3 is equivalent to the relative N recovery in the crop-soil system at time infinite (or $100–A_3$ is equivalent to the total losses of the fertilizer N applied). B_3 and C_3 are curve-shaping parameters.

Three to eight cropping seasons after an application of labelled fertilizer, N recovery in the crop-soil system ranged from 15 to 55% of the fertilizer N applied (losses varied between 45 and 85% of the fertilizer N applied) when crop residues were added, and from 13 to 66% (losses between 34 and 87%) when no crop residues were added. When N was applied via crop residues, recoveries in the crop-soil system ranged from 1 to 37% (losses between 63 and 99%).

The parameters that yielded the best fit for the $N_{1,j}$ (relative N retention in soil by the end of cropping season j) curves are listed below:

Case	T1				T2				T4			
	A_1	B_1	C_1	r^2	A_1	B_1	C_1	r^2	A_1	B_1	C_1	r^2
BGD	0.00	0.69	0.75	0.45	0.00	0.06	1.50	0.30	0.00	0.74	0.73	0.67
BRA	0.00	4.83	0.41	0.98	0.00	1.83	0.45	0.99	0.00	5.36	0.01	0.95
CHIma	0.00	0.67	2.08	0.85	–	–	–	–	0.00	0.37	2.59	0.81
CHIwh	0.00	1.50	1.49	0.84	0.00	0.19	0.01	0.00	0.00	1.27	1.65	0.66
CPR	0.00	2.39	0.01	0.82	0.00	0.17	0.36	0.09	0.00	2.86	0.01	0.93
EGY	0.00	2.83	0.53	0.93	0.00	0.64	1.07	0.92	0.00	2.88	1.05	0.98
MAL	0.00	1.13	0.83	0.79	0.00	0.82	0.01	0.25	0.00	1.76	0.40	0.68
MORfw	0.00	1.20	0.37	0.92	0.00	1.26	0.45	0.95	0.00	1.45	0.33	0.95
MORsw	0.00	1.26	0.01	0.91	0.00	0.97	0.21	0.85	0.00	0.84	0.32	0.92
MORww	0.00	3.59	0.01	0.90	0.00	0.51	1.52	0.79	0.00	3.97	0.01	0.88
SRLa	0.00	1.51	1.17	0.95	0.00	3.81	0.74	0.98	0.00	0.61	1.64	0.86
SRLb	0.00	1.31	1.20	0.95	0.00	7.51	1.37	1.00	0.00	1.43	1.49	0.97
VIE	0.00	3.66	0.34	0.93	0.00	0.51	0.01	0.45	0.00	1.40	0.98	0.92

A_1 values were 0 for all cases, and they represent the extreme values of the modelled curves, indicating that no fertilizer N (of a given application) will be left in soil at time infinite.

3.2. Model performance and fate of the fertilizer N applied

The descriptive model run generated curves representing the fate of fertilizer N in the soil, crop, and crop-soil compartments (Figs. 2–14).

The generated curves showed similar patterns for all cases studied (thirteen data sets): major losses of the fertilizer N occurred during the first cropping season, and then only small losses occurred in the following cropping seasons.

After a few seasons, the rate of decrease of the fertilizer N applied to the soil became virtually nil, showing that the N was probably immobilized in a stable organic form. It is interesting to note that a significant proportion of SOM is believed to have a residence time of 10 to 50 years (a slow turnover rate), while less then 10% of total SOM is believed to be active (microbial biomass and labile OM) and of significance in supplying minerals to plants [2].

Even though some marked effects of adding crop residues to the soil on the fate of the residual N following an input of N via inorganic fertilizers were expected, results from the thirteen data sets—collected in nine countries covering a wide range of soils, crop rotations, and climates—showed barely noticeable effects (T1×T4). The use of ^{15}N may underestimate N-recovery rates due to a dilution effect, since the N pool in soil is much larger than the amount of ^{15}N applied as a tracer for fertilizer N [3], which may explain the results. Other probable reasons should be further studied.

When N was applied via crop residues (treatment T2), it behaved in a very different manner. Retention in soil was much greater than when N was applied via inorganic fertilizers, but the recovery in the crop-soil system was poor due to a very low uptake rate by the crop. There was probably poor synchrony between N release from the residues and N demand by the crop.

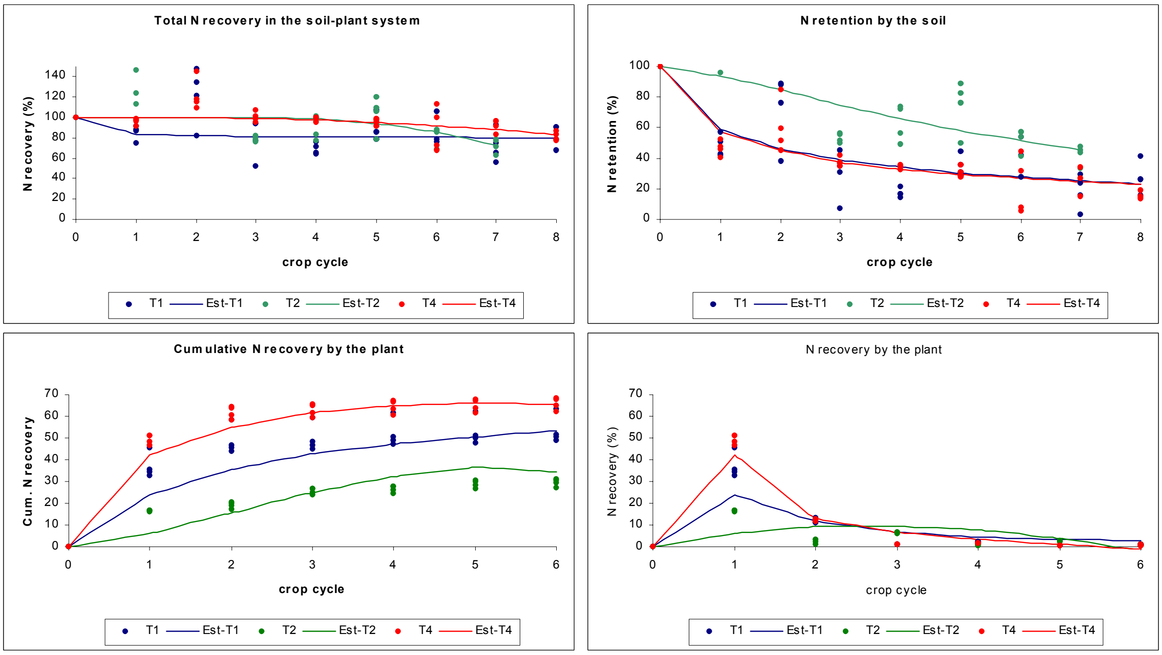

FIG. 2. Bangladesh: Fate of fertilizer N in a wheat-rice rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

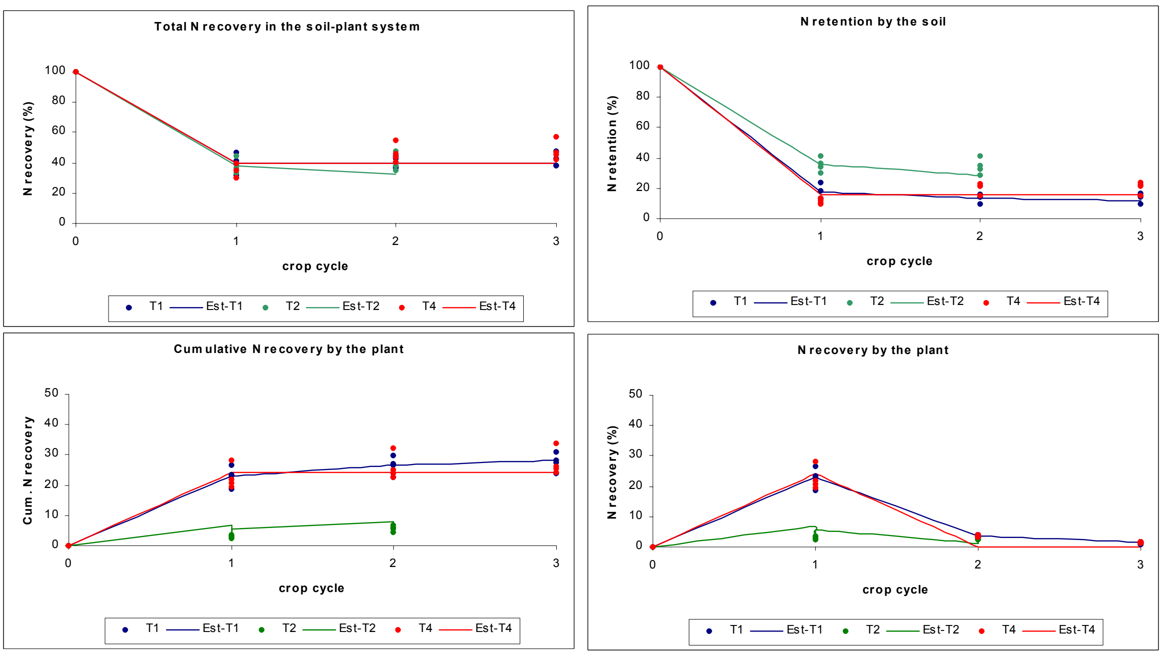

FIG. 3. Brazil: Fate of fertilizer N in a sugarcane monoculture. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

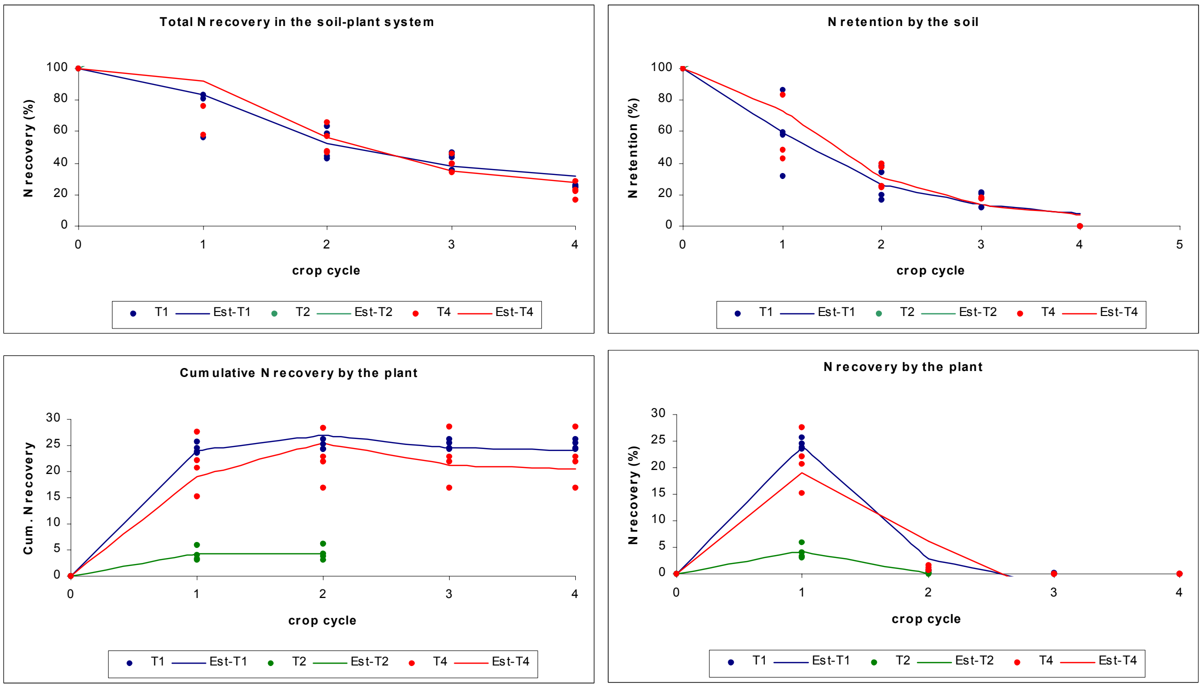

FIG. 4. Chile: Fate of fertilizer N in a maize-wheat-common bean-barley (or maize-wheat-red clover-red clover for T2 and T4) rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

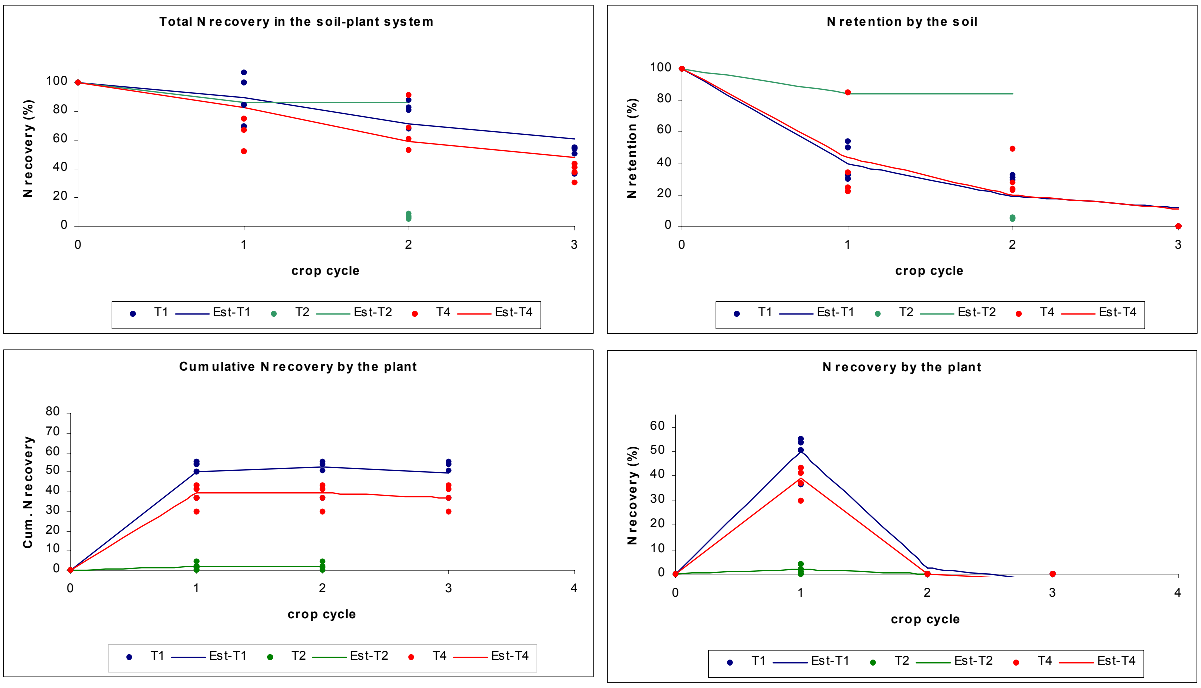

FIG. 5. Chile: Fate of fertilizer N in a maize-wheat-common bean-barley rotation (or maize-wheat-red clover-red clover for T4). T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

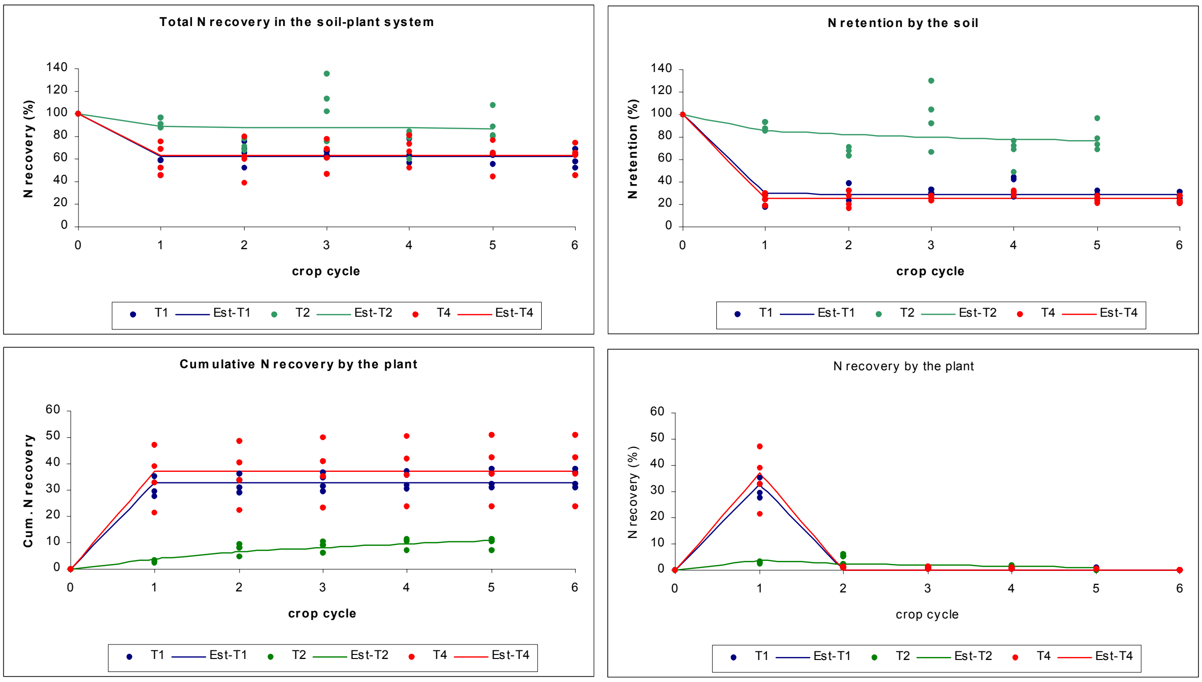

FIG. 6. China: Fate of fertilizer N in a rice-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

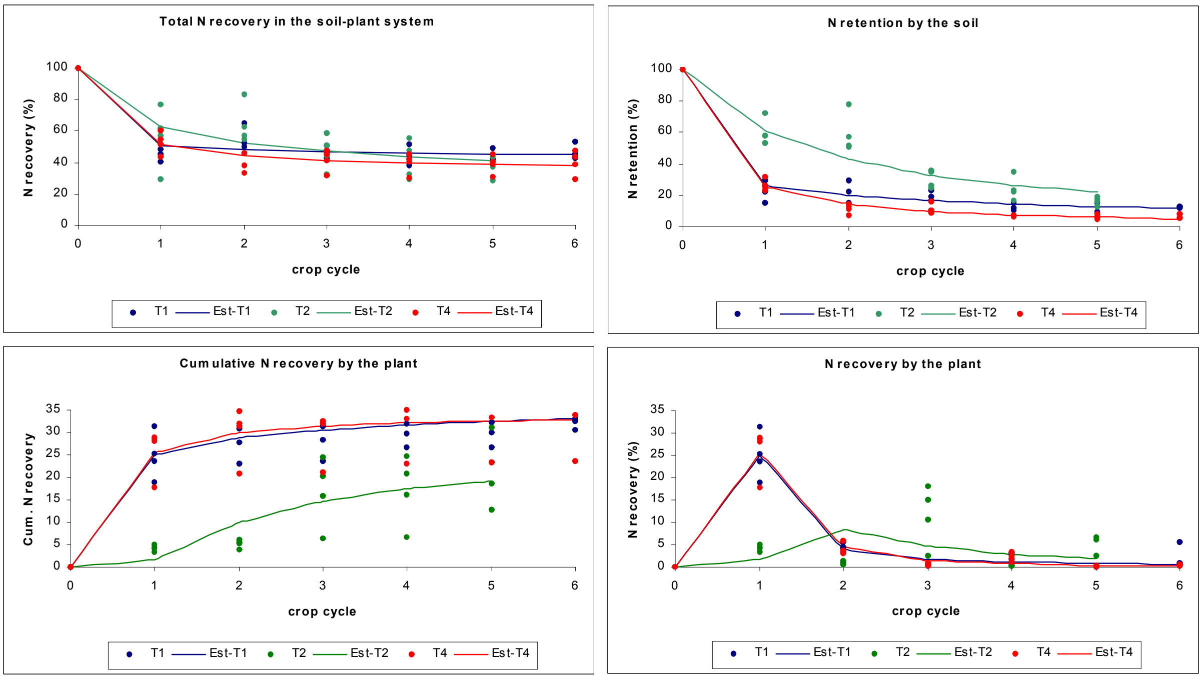

FIG. 7. Egypt: Fate of fertilizer N in a groundnut-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

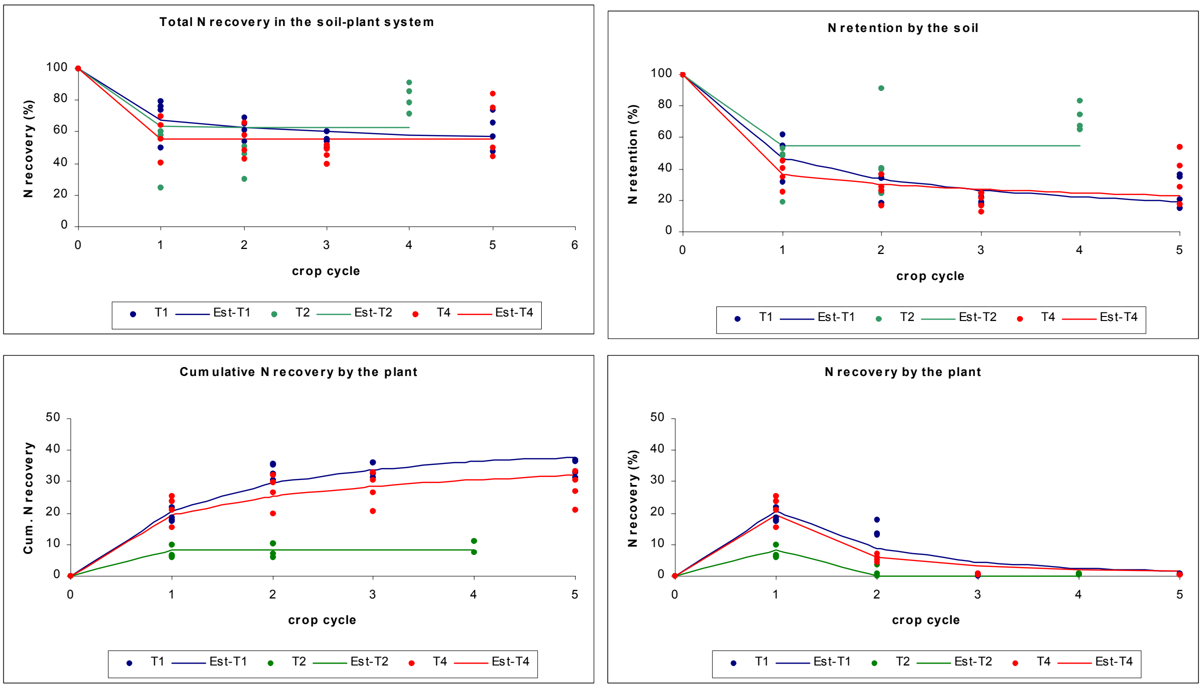

FIG. 8. Malaysia: Fate of fertilizer N in a maize-groundnut rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

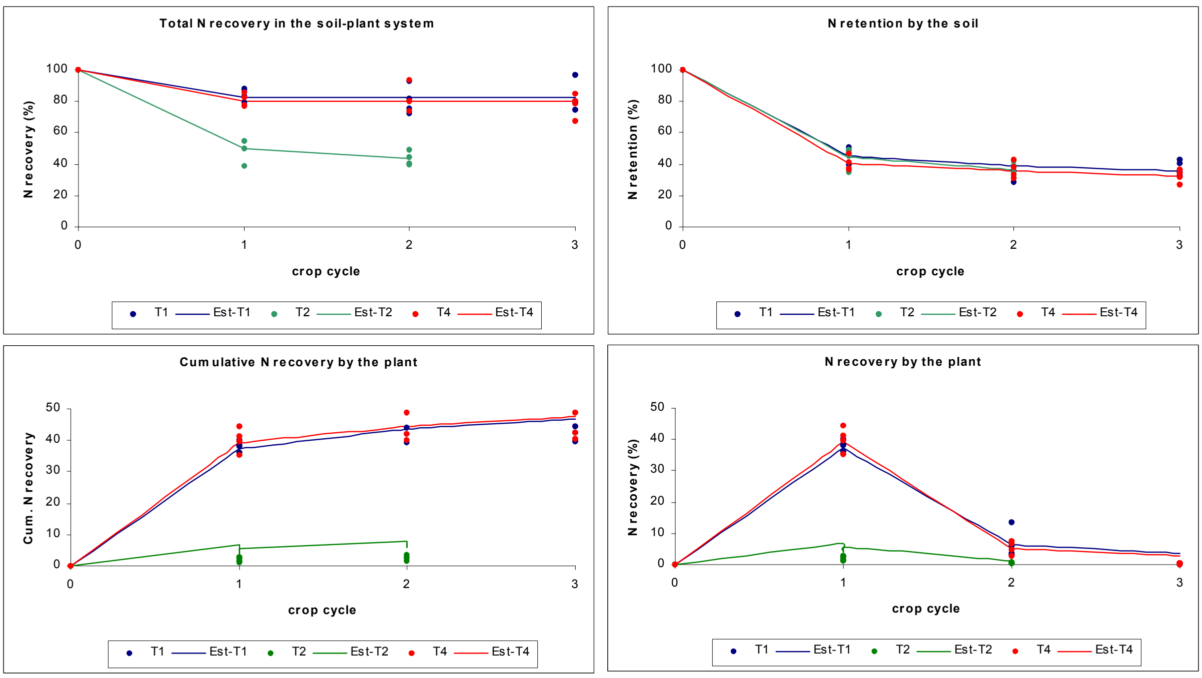

FIG. 9. Morocco: Fate of fertilizer N in a faba bean-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

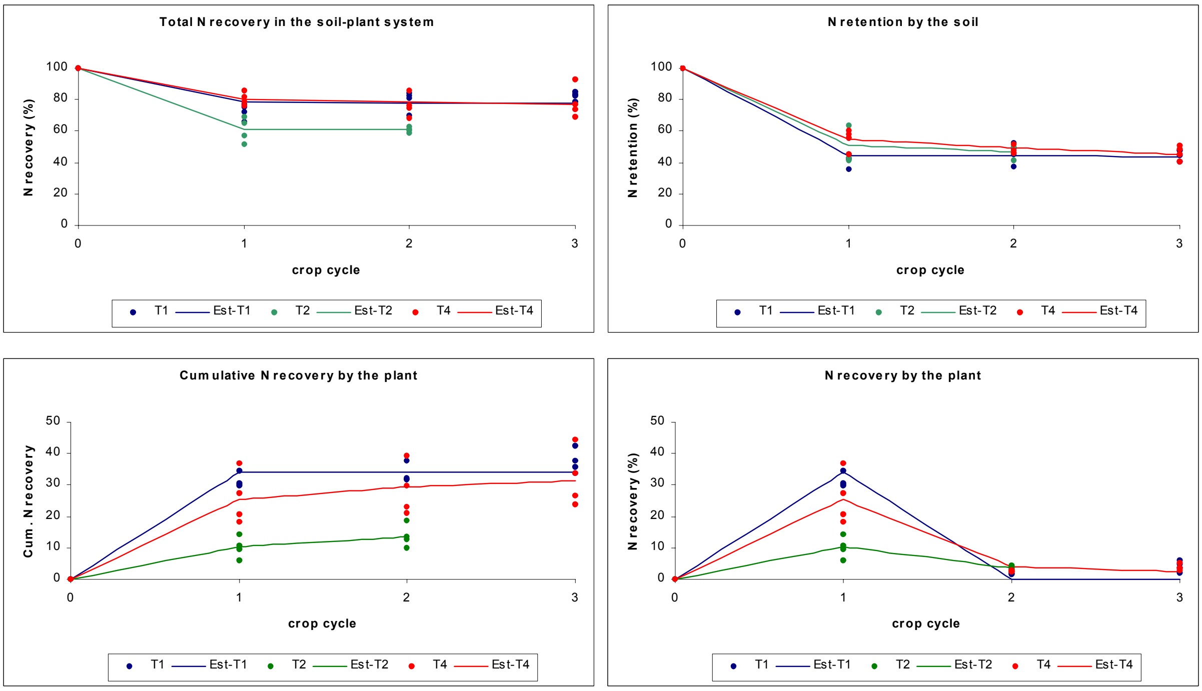

FIG. 10. Morocco: Fate of fertilizer N in a sunflower-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

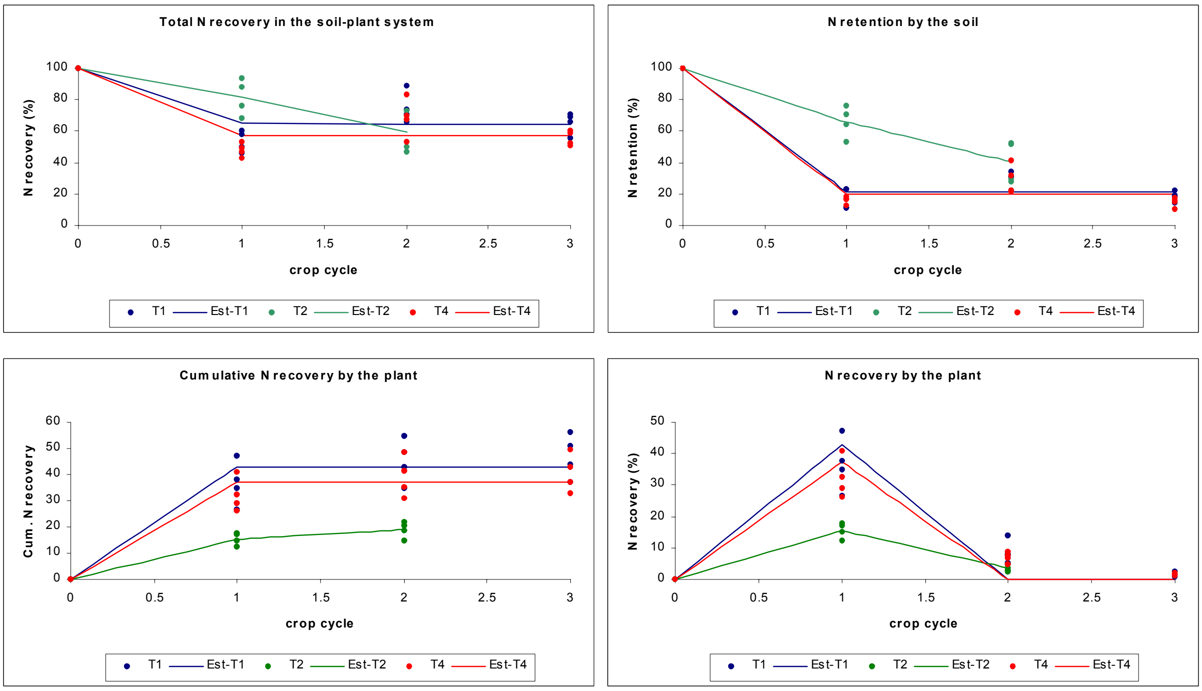

FIG. 11. Morocco: Fate of fertilizer N in a wheat monoculture. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

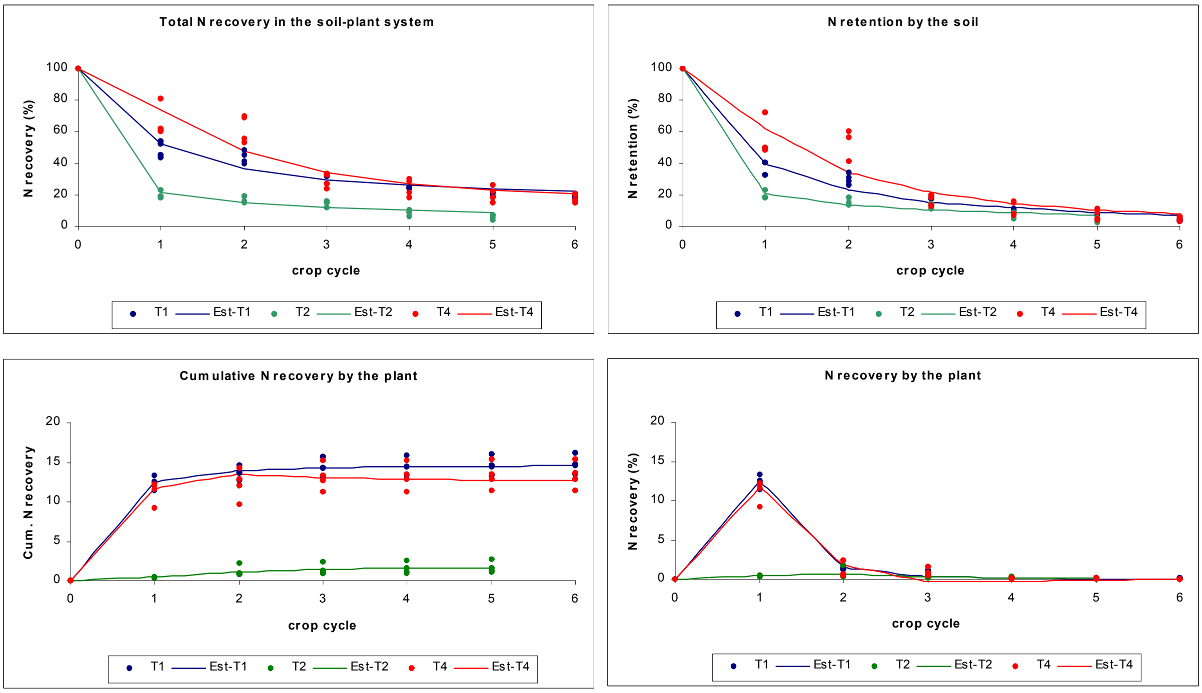

FIG. 12. Sri Lanka: Fate of fertilizer N in a mung bean-maize rotation, starting in the dry season. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

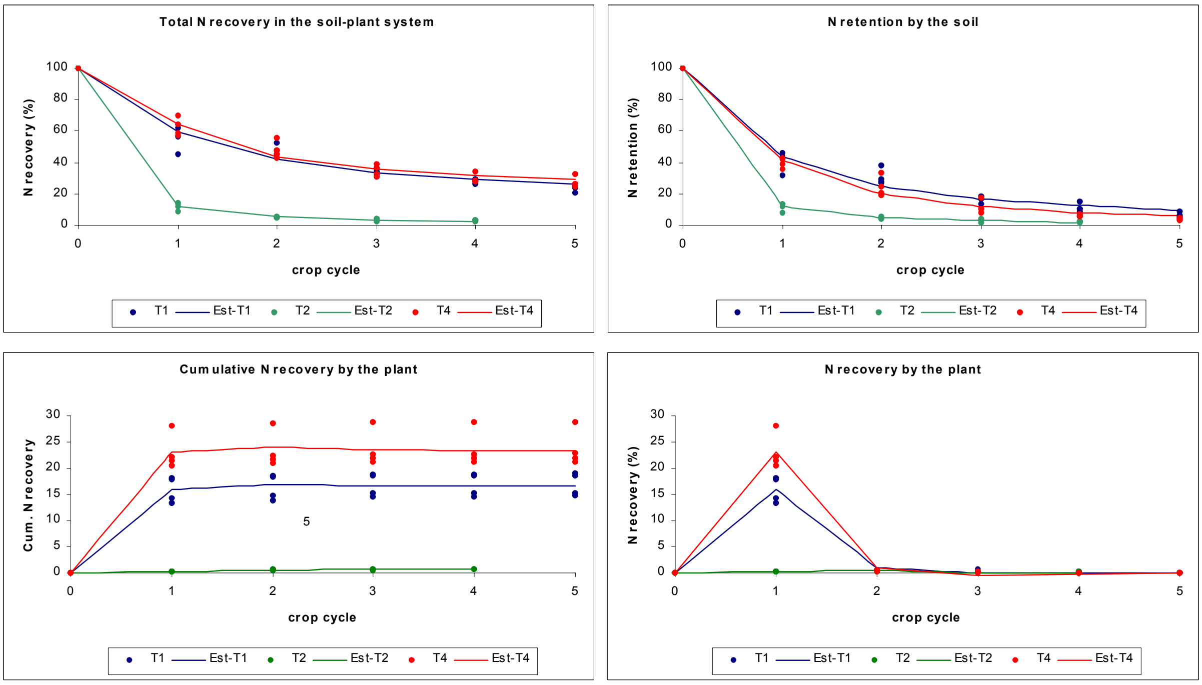

FIG. 13. Sri Lanka: Fate of fertilizer N in a mung bean-maize rotation, starting in the wet season. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

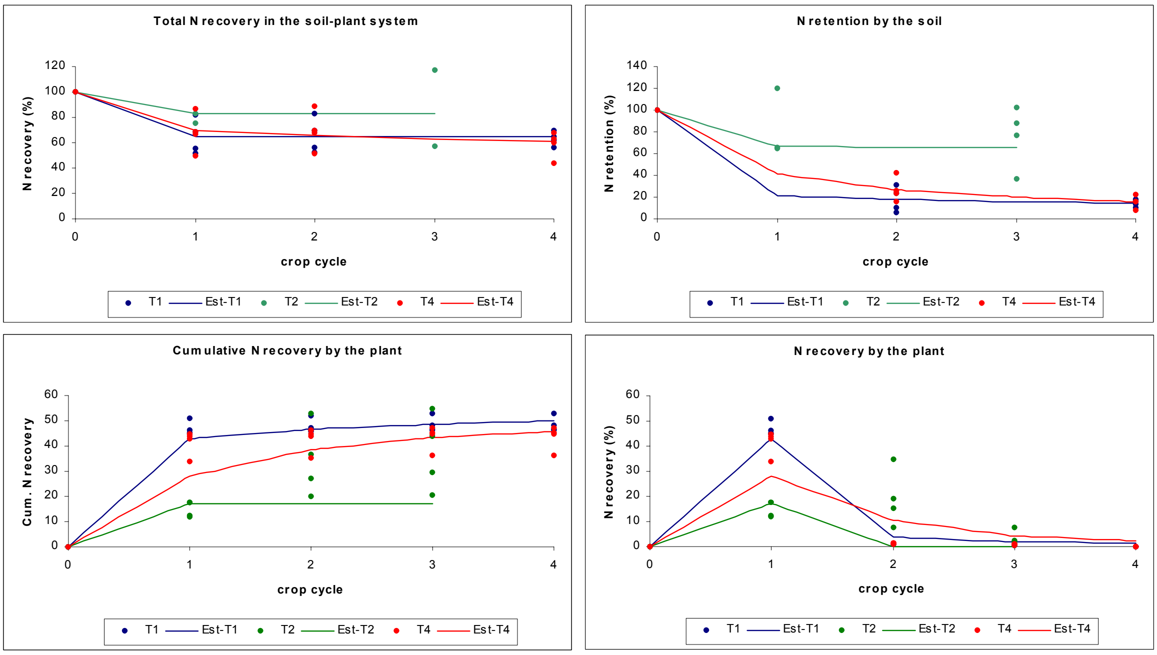

FIG. 14. Viet Nam: Fate of fertilizer N in a maize-soybean rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates, and lines represent estimated N fate according to the descriptive model.

4. CONCLUSIONS

The proposed model described well the fate of fertilizer N in all compartments (soil, crop, and crop-soil), generating curves that allow easy visualization in every case studied. Thus, the descriptive model proposed in this study proved to be an efficient tool for making comparisons between treatments and between sites.

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