IAEA-TECDOC-1354

Management of crop residues for sustainable crop production

Results of a co-ordinated research project organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture 1996–2001

INTERNATIONAL ATOMIC ENERGY AGENCY

May 2003

The originating Section of this publication in the IAEA was:

Soil and Water Management & Crop Production Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

MANAGEMENT OF CROP RESIDUES FOR SUSTAINABLE CROP PRODUCTION
IAEA, VIENNA, 2003
IAEA-TECDOC-1354
ISBN 92–0–104203–5
ISSN 1011–4289

Printed by the IAEA in Austria
May 2003

FOREWORD

It is well recognized that the organic matter content of a soil is a key attribute of fertility. The beneficial effects of organic matter on the physical, chemical, and biological properties of soil are well documented. Decline in organic matter content in intensive cropping systems is considered to be the major problem in maintaining agricultural productivity in the tropics. Additions of organic materials such as crop residues play an important role in the recycling of nutrients. More than one half of all dry matter in the global harvest is in the form of residues, and in most developing countries the amounts of nutrients in residues are often several orders of magnitude higher than the quantities applied as fertilizers. Thus, proper management of crop residues for the maintenance of soil fertility cannot be overstressed. This Co-ordinated Research Project (CRP) focused on countries where crop production and soil fertility can be sustained by the better management of crop residues.

As a result of recommendations formulated at a consultants meeting organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, 4–7 September 1995, a Co-ordinated Research Project on "The Use of Isotope Techniques in Studies on the Management of Organic Matter and Nutrient Turnover for Increased Sustainable Agricultural Production and Environmental Preservation" was implemented between 1996 and 2001. The overall objective of the CRP was to increase crop production through better management of soil organic matter and nutrient inputs.

Ten contract and five agreement holders from Australia, Bangladesh, Belgium, Brazil, Chile, China, Egypt, India, Malaysia, Morocco, Mexico, Sri Lanka, the United Kingdom, the United States of America and Viet Nam participated in the project. The first Research Co-ordination Meeting (RCM) was held 7–11 October 1996 in Vienna. Subsequently, RCMs were held 20–24 April 1998 in Vienna, 6–10 September 1999 in Rabat, Morocco, and 26–30 March 2001 in Serdang, Malaysia.

This technical document contains the manuscripts prepared by the project participants, and was edited by A.R.J. Eaglesham, Ithaca, New York. The IAEA officer responsible for this publication is G. Keerthisinghe of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

EDITORIAL NOTE

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SUMMARY

Since ancient times, farmers have recognized the importance of organic matter inputs to enhance crop yields. Organic matter contributes to plant growth through beneficial effects on the physical, chemical, and biological properties of the soil, including (i) provision of a carbon and energy source for soil microbes, (ii) improvement of soil aggregation, thus reducing the hazard of erosion, (iii) retaining of nutrients and water, (iv) provision of nutrients through decomposition, and (v) reduction of soil compaction. The amount of soil organic matter is controlled by the balance between additions of plant and animal materials and losses by decomposition. Both additions and losses are directly affected by management practices. For example, replacing perennial vegetation with short-season vegetation and the burning of crop residues result in a reduction in organic inputs to the soil, while application of animal and crop residues, use of cover crops, and reduced tillage increase inputs or reduce losses and hence help to maintain or increase soil organic matter content. Under tropical conditions, organic matter is rapidly lost through accelerated oxidation due to hot and moist conditions. Rapid losses can be arrested through appropriate agronomic practices that include retention of crop residues.

This CRP supported national efforts in eleven Member States to identify options managing crop residues for sustainable agricultural production and environmental preservation in a wide range of soils and cropping systems. Various options for the recycling of crop residues that are sustainable and economically attractive to farmers were examined using isotopic techniques. The specific objectives of this CRP were:

— to increase the quantity of nutrients available to crops from organic sources and for more-effective recycling of those nutrients,
— to enhance the efficiency of use of nutrients by crops, and minimize losses through improved synchrony between nutrient supply and crop demand, and
— to improve process-level understanding of carbon and nutrient flows through the use of isotopic techniques so that management recommendations can be extrapolated to a wide range of environments using models.

The field experiments of this CRP were conducted in various agro-ecological regions under several cropping systems. All experiments were conducted according to an agreed protocol, but the design allowed flexibility to adjust treatments and management practices to suit the conditions and cropping systems. Some counterparts included additional treatments such as different tillage systems (Mexico) and addition of animal manure (Malaysia), and some extended the experiments to more than one location (Morocco and Viet Nam). The nitrogen (N) added to soil as ^{15}N-labelled fertilizer ranged from 35 to 300 kg N ha^{-1}, and the residue additions ranged from 12 to 160 kg N ha^{-1}. The fate of applied N was followed through the following treatments: (i) ^{15}N-labelled fertilizer with unlabelled crop residues, (ii) unlabelled fertilizer with ^{15}N-labelled crop residues, and (iii) ^{15}N-labelled fertilizer without residues.

A simple mathematical model, descriptive in nature, was developed to synthesize information collected from all experimental sites, allowing comparisons between treatments and sites. The descriptive model generated curves representing the fate of fertilizer N in soil and crop under various management practices. In synthesis, the results obtained under varying cropping systems and agro-climatic conditions over a period of five years showed that only about 35% of the applied fertilizer N was recovered by the crops during the first season. During subsequent seasons, insignificant amounts of N (<4%) were recovered from the residual fertilizer. Application of residue had no significant effect on N uptake by crops. Experiments conducted using labelled crop residues showed high variability in availability of residue N to crops. The availability was rather low, less than 10% during the first season, and declined rapidly during subsequent seasons. The slow release of N from residues and lack of synchrony between N demand by the crop and N release resulted in poor recovery of residue N.

Most of the fertilizer N was lost during the first cropping season and only insignificant losses occurred in the following seasons. The losses of N from applied fertilizer ranged from 45 to 85% irrespective of crop-residue management practice. More than 30% of N was lost from crop residues. When N was applied as crop residues, its retention in the soil was higher than for fertilizer N, but its recovery by plants was poor, as mentioned above. These results highlight the importance of investigating fertilizer-management practices to minimize the losses, especially during the early part of the cropping season.

Application of straw resulted in increases in grain yields of rice and wheat of about 10% in experiments conducted in China. However, in general, addition of straw did not increase crop yields in other locations. This is encouraging, as initial immobilization of N due to application of high inputs of carbon through residues did not exhibit negative effects on crop yields.

The experiments in India demonstrated simple practices, using wheat and rice residues, to produce compost as an alternative to stubble burning. Such practices can have important implications apart from the desired maintenance of soil organic matter and improving plant growth. For example, approximately 12 million tonnes of rice and wheat straw are burnt annually in Punjab, India, causing atmospheric pollution and producing over 28 million tonnes of carbon dioxide, a greenhouse gas. In addition, various gaseous forms of N are emitted during burning, representing a loss of $17 million in fertilizer equivalents and significant pollution of the environment by nitrous oxide.

The results obtained from crop-residue application studies are of importance for residue-management practices. There is an increasing need for such information as in many countries new legislation has been introduced to ban the on-site burning of crop residues, for environmental reasons. Moreover, this CRP demonstrated the use of ^{15}N techniques for investigating the fate of N in crop residues and fertilizers under different management practices and cropping systems, which will be useful for other related CRPs on agroforestry, rainfed and rice-wheat cropping systems co-ordinated by the Soil and Water Management & Crop Nutrition Section, where management of crop residues and fertilizer plays a major role in increasing crop yields.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

— New legislation that has been introduced in many countries to ban the on-site burning of crop residues necessitates the introduction of innovative residue-management strategies.
— The bio-physical properties of soils were improved by incorporation of crop residues, indicating the importance of considering the non-nutritional benefits of residue management.
— Addition of crop residues did not lead to higher yields.
— Addition of carbon through residues did not result in higher N-retention in soils.
— Although total recoveries of residue N in the soil and crop were expected to be higher than for fertilizer N, results showed otherwise.
— The residual effects of fertilizer N and crop-residue N were negligible, which should be taken into account in fertilizer-recommendation studies.
— Approximately two-thirds of fertilizer N was lost irrespective of residue-management practice highlighting the need for further studies on management of N fertilizers.
— An explanatory model was developed for synthesis and evaluation of data obtained from varying agro-ecological regions to obtain meaningful information on residue-management practices.
— Long-term studies are needed to investigate the effects of various residue-management practices on carbon sequestration, weed and pest management, chemical and bio-physical parameters of soils and their effects on crop yields.

RECYCLING OF CROP RESIDUES FOR SUSTAINABLE CROP PRODUCTION IN A MAIZE-GROUNDNUT ROTATION SYSTEM

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Abstract

A long-term field experiment, which was established to investigate the contribution of crop residues to the N-economy of a maize-groundnut rotation system, consisted of three treatments: (i) T1, the recommended rate of chemical fertilizer with residue, (ii) T2, the recommended rate of chemical fertilizer without residue, and (iii) T3, a combination of organic fertilizer (chicken manure) and chemical fertilizer with residue. In order to investigate the N contribution from residues of the first crop (maize) to subsequent crops, the maize was labelled with ^{15}N in the T1 and T2 treatments. Fertilizer N (^{15}N-ammonium sulphate, 9.82% a.e.) was applied (60 kg N ha^{-1}) to microplots within each yield plot, to generate labelled maize residue. At the same time 90 kg N ha^{-1} unlabelled N fertilizer was applied to provide the recommended rate for maize of 150 kg Nha^{-1}. Uptake of N and K by subsequent crops was significantly higher in crop-residue treatments, whereas uptake of P, Ca and Mg was not significantly affected. Soil pH, organic C, cation-exchange capacity, soil resistance, water content and bulk density were not significantly changed after four crop-residue applications. Soil organic matter size and density fractions seemed to increase, with application of residues, but without statistical significance. Soil available P and exchangeable K were significantly higher in plots with crop residues. Recovery of fertilizer ^{15}N by the first crop ranged from 19 to 22%. In the following crop, the recoveries were only 5.1% and 5.6% in plants of T1 and T2 treatment and only trace recoveries of ^{15}N occurred in the subsequent crop. Fertilizer ^{15}N retained in the soil after harvest of the first crop was 35 to 44%, whereas after the second crop 33% was present in crop-residue treated plots and 26% in plots where crop residues had been removed. Nitrogen mineralization from maize residues was quite rapid from 4 to 8 weeks after incorporation due to the hot, humid conditions. Thus, for good synchrony of release of N from residues and uptake of N by the crop, sowing should be 4 to 6 weeks after residue incorporation. However, in a rain-fed area it is sometimes inevitable that fallow periods are long, i.e. more than 6 weeks, depending on the rainfall, as in this study. Contributions of crop residues to economic yields were not significant, even after six crop cycles.

1. INTRODUCTION

Organic matter plays a key role in maintaining the fertility of acid soils since the clay mineral is mainly kaolinite as a result of intensive weathering under high precipitation [1,2]. Until recent years, common agricultural practices have resulted in the depletion of inherent soil nutrients due to leaching and continuous removal by crops. Burning is a common practice on Malaysian farms, thought to be necessary to facilitate planting and to control weeds and pests. This results in loss of the C and N sequestered in the biomass, it pollutes the air and contributes to global warming by CO_2 evolution [3]. Continuous cropping of the land causes declines in soil organic matter and loss of inherent fertility. Therefore, large inputs of chemical fertilizer are necessary to sustain crop yields. However, with recent implementation of environmental policies by the government and increasing awareness of the benefits and importance of soil organic matter in sustaining crop production, agro-industrial wastes and crop residues are being returned to, or left in, the field as soil ameliorants and sources of nutrients. Rotations with legumes that are efficient in fixing atmospheric N_2 and in returning N to the soil through crop-residue incorporation have been widely studied elsewhere [4,5]. However, in Malaysia, the potential importance of such systems has been overlooked.

Maize is currently an important crop for fresh consumption as snaclis and for poultry feed. It is grown mainly as a continuous monocrop, although greater sustainability is possible in rotations with legumes. There is poor understanding of the contributions to soil fertility and crop yields when residues are left in the field during the fallow period.

The objectives of this study were to investigate:

— the effects of crop-residue application on yields in a maize-groundnut rotation system,
— the fate of ^{15}N-labelled fertilizer and effects of crop-residue incorporation on soil organic matter and soil chemical properties of an Ultisol, and
— decomposition of crop residue and mineralization of N and other nutrients from ^{15}N-labelled maize residues during fallow.

Table I. Physico-chemical properties of the soil

Variable	Depth (cm)		
	0–20	20–40	40–60
$pH_{(H_2O)}$	5.30	4.90	4.79
Mineral N (µg g^{-1})	7.90	10.5	8.70
Organic C (g kg^{-1})	16.6	10.1	6.70
TN (g kg^{-1})	1.77	1.25	1.10
Available P (µg g^{-1})	12.6	7.88	2.53
K (cmol (+) kg^{-1})	0.12	0.09	0.06
CEC (cmol (+) kg^{-1})	6.86	5.51	4.18
Bulk density (g cm^{-3})	1.28	1.49	1.61
Sand (%)	62	59	55
Silt (%)	4.6	3.9	3.7
Clay (%)	34	37	42
Texture	SCL[a]	SCL	SCL

[a]Sandy clay loam.

Table II. Treatments for the main field experiment and rates of fertilizer application

Treatment	Chicken dung (t ha^{-1})	$(NH_4)_2SO_4$ (kg N ha^{-1})		TSP (kg P ha^{-1})	KCl (kg K ha^{-1})
		Labelled (^{15}N)	Unlabelled		
		Maize			
T1[a]		60	90	90	90
T2[b]		60	90	90	90
T3[c]	10		75	45	45
		Groundnut			
T1[a]			30	90	90
T2[b]			30	90	90
T3[c]			30	90	90

[a]Recommended chemical fertilizers with residue applied after each harvest.
[b]Recommended chemical fertilizers without residue (control).
[c]Combination of ½ rate of recommended chemical fertilizers, chicken manure and residue. (composition of manure: 23.6, 31.2, 35.3, 34.9, 141, and 20.1 g kg^{-1} for N, C, P, K, Ca, and Mg, C/N ratio of 9.6).

2. METHODOLOGY

2.1. Effects of crop-residue recycling on maize and groundnut yields and the fate of fertilizer N

The field experiments were laid out at the Universiti Putra Malaysia experimental station in Puchong, about 5 km from the university. The soil is classified as Bungor series, a clayey, kaolinitic, isohyperthermic Typic Paleudult (Table I). Three treatments (Table II) were laid out in a randomized complete block design (RCBD) with four replications. Treatments T1 and T2 were applied with ^{15}N-labelled fertilizer at sowing of the first crop (maize) to follow the fate of fertilizer-N through the above- and below-ground components. Treatment T3 was included as an alternative management practice to provide comparisons of yields and effects on soil properties.

2.1.1. Field procedures

Each treatment was applied to mains plots of 8.0×20.0 m. To study the fate of applied ^{15}N (below ground) with or without crop residues, microplots of 4.0×4.0 m were established within each main plot of T1 (T1A) and T2. Similarly, to trace the fate of ^{15}N in the first-crop (maize) residue T1B, microplots were also established in T1 plots. The basic layout is given in Fig. 1. Processed chicken manure (23.6, 31.2, 35.3, 34.9, 141 and 20.1 g kg^{-1} of N, C, P, K, Ca and Mg, respectively) was applied at 10 t ha^{-1} before sowing the maize. Two ton ha^{-1} of lime in the form of ground magnesium limestone (GML) was applied 1 month before sowing each crop. To follow the fate of fertilizer N in the cropping system, $(^{15}NH_4)_2SO_4$ (9.82 at. % ^{15}N excess) was applied at 60 kg N ha^{-1} to microplots of treatments T1 and T2 in the first crop. To ensure homogeneous distribution of the labelled fertilizer, it was dissolved in water and applied in four split applications at 2, 4, 6, and 8 weeks after sowing. Maize and groundnut varieties used were Manis Madu and Matjan, sown at spacings of 75×25 cm and 50×20 cm, respectively. Before sowing groundnut, the seeds were treated with inoculant (*Bradyrhizobium* strains NC92 and CB756 mixed 1:1 with choir dust) at the rate of 250 g kg^{-1} seed. Weeds were managed with gramazone, and fungal diseases were avoided by mixing the seeds with captan. Maize was harvested about 75 days after sowing. Ears were collected from each main plot and graded according to weight as A (>180 g), B (80–180 g), or C (<80 g). Ears of grades A and B were considered as economic yield (i.e. marketable fresh yield). For determination of total dry-matter yield, the weights of all three grades were added to that of the stover.

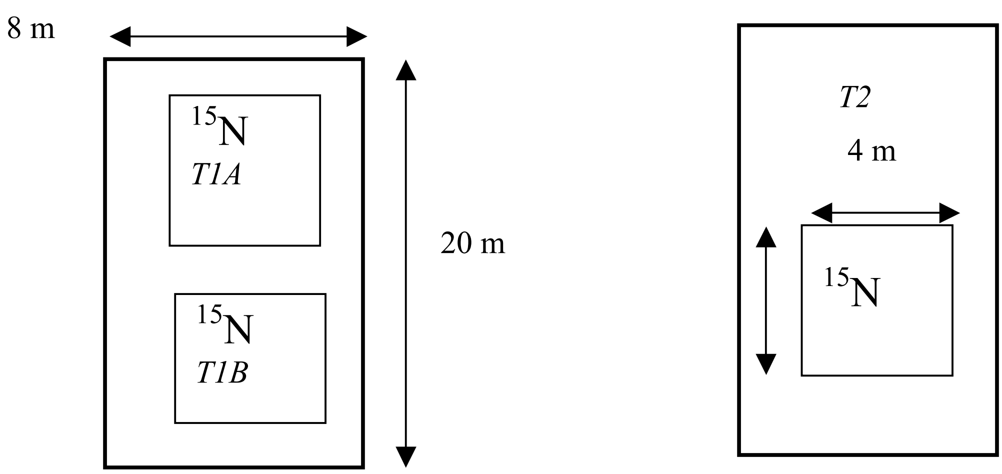

FIG. 1. Layout of plots and microplots in the T1 and T2 treatments.

Table III. Dry matter and nutrient contents of maize stover and groundnut haulms added as residue

Treatment	First crop	Second	Third	Fourth[a]
	(kg ha^{-1})			
	Dry matter			
T1	3,711	5,101	4,230	2,688
T3	2,374	5,591	4,429	2,875
	N			
T1	51.0	121	66.6	72.0
T3	31.8	131	78.4	72.7
	P			
T1	5.73	10.3	11.3	7.50
T3	4.67	10.9	11.4	10.1
	K			
T1	48.1	149	76.1	57.9
T3	62.5	122	125	67.4
	Ca			
T1	19.0	68.1	20.5	24.8
T3	10.2	67.0	18.5	30.5
	Mg			
T1	13.1	54.6	25.2	10.2
T3	7.79	50.2	20.3	11.3

[a]Plants damaged by wild boar.

Groundnut was harvested as fully mature pods and weighed in the field to obtain the economic yield. For comparison, economic yield of the sixth crop (groundnut) was included. At harvest, eight maize and groundnut plants were harvested from the inner 2.0×2.0-m areas of the microplots. Maize plant were separated into stover and ears (husk + cob + grain). The groundnut plants were separated into above-ground parts (haulms) and pods. Plant samples were chopped into small pieces, sub-sampled, dried in the oven (65–70°C), ground, and stored for analyses of N [6], P and K [7].

During the first crop (maize), surface (0–15 cm) samples of soil were taken from the main plots with a 5.0-cm-diameter auger at sowing and silking for determination of total soil mineral N (TSMN, i.e. (NH_4^+ and NO_3^- + NO_2^-). At harvest, soil samples were taken at three depths (0–15, 15–30 and 30–50 cm) from four points in the inner (2×2-m) areas of the microplots and mixed into a composite sample. Thereafter, soil samples were taken regularly at sowing (0–15 and 15–30 cm) from main plots and at harvest from microplots (0–15, 15–30 and 30–50 cm).

Immediately after harvest, the crop residues (maize stover and groundnut haulms) from each microplot were recorded (Table III). After harvest of the first crop, labelled maize residues were removed from microplots of T1. For T2 (control), both labelled (from microplots) and unlabelled (from main plots) residues were removed. The aim with the ^{15}N microplots in T2 was to follow the fate of below-ground (fertilizer and root) ^{15}N in the subsequent crop-soil system without crop residues. The labelled residues from the first maize crop from microplots T1A were transferred to a new microplot (T1B) in the same plot (T1) to follow the fate of N mineralized from the labelled above-ground first-crop residue in the subsequent crop-soil system. Unlabelled residues in the main plots of T1 were left on the surface. An amount equivalent to the labelled residue removed from microplot T1A was replaced as unlabelled residues removed from the main plots of T2. The aim with the T1A microplots was to follow the fate of the below-ground fertilizer N in crop residues. In the subsequent crops, after each harvest, all labelled residues obtained from T1A and TIB were removed and replaced with unlabelled residues.

For all soil samples, fresh samples were used for determination of TSMN [8] and the rest was dried, ground to pass through a 2.0-mm sieve and analysed for pH (H_2O), total N [6], organic C [9], available P [10], and CEC [11]. Size [12] and density [13] fractionation of SOM was carried out for topsoil (0–15 cm) samples collected at sowing and harvest of the second and fourth crops. The fractions were dried at 65 to 70°C, weighed, ground (0.5 mm) and analysed for C and N.

2.2. Decomposition of maize ^{15}N residues and uptake by subsequent groundnut

2.2.1. Experimental layout

This study was carried out simultaneously with the main field experiment during the fallow period. After the first maize crop was harvested, the experiment was laid out as before and extended into the subsequent crop cycle. Decomposition (for 21 weeks) of ^{15}N-labelled maize residues and nutrient release were studied using polyvinyl chloride tubes (16 cm in diameter and 40 cm long). After harvesting the maize ears, the standing crop was slashed 5 cm above the ground and some residues were taken for the decomposition study. Ninety-six tubes were driven into the soil of T1, T2 and T3 plots (eight tubes per plot) leaving about 5 cm above the ground. Fresh-maize residues with 1.766% a.e. ^{15}N and 13.5, 2.9 and 14.9 g kg^{-1} N, P and K, respectively, and C/N ratio of 40, were chopped into pieces of about 1.0 to 2.5 cm in length and placed on the soil surface in the tubes installed in T1 and T3 while the tubes in T2 were kept as controls. Crop-residue application rates (based on stover yields) ranged from 1.30 to 3.03 t ha^{-1} dry matter (average 2.17 t ha^{-1}). At week 12 after residue application, lime was applied at the rate of 2.0 t ha^{-1} to all plots, including the tubes, i.e. 1 month before sowing the subsequent groundnut crop. After liming, the plots were cultivated with a hand-driven plough. Ploughing was simulated within the tubes. The tubes were removed at 2-week intervals for the first 3 months and then at 3-week intervals. At each sampling, four tubes were removed, placed in a plastic bag and transferred to the laboratory. The crop residue on the surface of each tube (up to 12 weeks) was collected carefully, washed with de-ionized water, dried on Whatman filter paper at 70°C to a constant weight, and the dry-matter weight (DMW) recorded. The tissue samples were then ground (0.5 mm) and analysed for organic C, N, P and K, as described earlier. The soil core in each tube was divided into two depths, 0 to 20 and 20 to 30 cm. Each depth was mixed thoroughly and a fresh sub-sample was taken for TSMN determination. Mineral N of soil samples taken after 2 weeks was not determined because the samples were already dried before sub-sampling. Net N mineralization or immobilization was calculated by subtracting mineral N in the control (T2) from those in the T1 and T3 treatments. For determination of decomposition rates, data obtained were subjected to the non-linear (NLIN) procedure of SAS for multiple regression models [14].

For investigation of groundnut growth rate and N uptake, an area of 0.5×1 m in each plot was sampled every 3 weeks until harvest (96 days). The harvested plants were divided into above-ground parts, roots, and pods (if any), oven dried, and analysed for N.

3. RESULTS AND DISCUSSION

3.1. Economic yield

Up to the fourth crop, there was no significant effect of crop-residue application on economic yield of the subsequent crops (Table IV). After incorporation of four crop residues, economic yield of the fifth crop (maize) showed significant ($P \leq 0.05$) differences between treatments. Yields from T3 plots were greater than those of the control (T2) by more than 100%. Application of crop residues of the fifth crop had no significant positive increase in economic yield of the sixth crop. Economic yields of the subsequent crops were consistent with those of another study [15] in which there were no significant effects of incorporating wheat residues on grain yields of irrigated continuous winter wheat over a period of 14 years. This was probably because the crop residues were applied 1 to 4 weeks after harvest and the subsequent crops were sown about 11 to 20 weeks after harvest. This fallow period may be too long for synchrony of nutrient release from the decomposing residues with demand by the subsequent crop.

Total N, P and K contents of the crops are given in Table V. There were no significant differences in total-N values between treatments in the first crop (maize), though it was observed that application of chicken manure (T3) increased total N uptake over T2 by 6 to 17%. Total N content of the third crop (maize) in T3 was significantly ($P \leq 0.05$) higher than that of the control (T2) by 67%. The amount of crop residues applied after harvest of the fourth crop (groundnut) was relatively low because of damage by wild boars. Consequently, total N content of crop residue applied in T1 was too small to affect N uptake by subsequent crops. For groundnut, application of maize stover had no significant effect on total N content. In general, lack of significant effects of groundnut haulms on N uptake by subsequent maize crops could be attributed to the longer fallow period (9–11 weeks) before sowing the maize.

In the Ultisols of the humid tropics of Thailand, an experiment was conducted to study the effect of incorporating (28 days before sowing) groundnut haulms of different varieties on yield of subsequent maize [4]. That study showed that total N content of maize in residue-treated plots was 23 to 72% higher than without. The slight increase in total N of the third maize crop reported in this study (22%) was lower than the lower range found in the previous study [4]. This could be attributed to their shorter fallow period (28 days) before sowing the maize, resulted in better synchrony of residue-N released and taken up by the subsequent crop. Although groundnut is an N_2-fixing crop and can meet its N requirement via this process, amelioration of acidic soils by incorporation of crop residues may improve fixation, hence increasing total N uptake.

During four-crop cycle, application of organic material (crop residues or chicken manure) in T1 or T3 had no significant effects on P content of the subsequent crops. However, in the fifth crop, the combined crop residues and chicken manure (T3) significantly increased P content. The increase over the control (T2) was 63% for total P content. Throughout the five crop cycles, application of residues with chemical fertilizer (T1) had no significant effect on P content of the subsequent crops. The significant P content in subsequent maize crops supplied with crop residues combined with chicken manure could be attributed to the additional amounts added in the manure (240–337 kg P ha^{-1}). Most of the P present in manure is available to a crop during a growing season of 3 to 4 months [16]. Low P content of the crop residues (4.7–11.4 kg ha^{-1}) probably explains lack of significant positive changes in P content of subsequent crops as compared to control plots (T2). This is consistent with the results of another study [17] in which there were no significant effects on P uptake by pearl millet (*Pennisetum glaucum*) for 4 years of recycling 4 t ha^{-1} of millet stover.

Table IV. Economic yields of maize and groundnut as influenced by crop-residue application

Trtmnt	First crop (Maize)	Second (Groundnut)	Third (Maize)	Fourth[a] (Groundnut)	Fifth (Maize)	Sixth (Groundnut)
	(t ha^{-1})					
T1	3.59a[b] (0.47)[c]	5.10a (0.11)	3.51a (0.53)	2.58 (0.62)	2.56b (0.92)	3.28a (0.34)
T2	3.20a (0.85)	4.90a (0.13)	2.65a (0.93)	2.25 (0.62)	2.55b (0.94)	3.07a (0.44)
T3	4.29a (0.80)	5.17a (0.18)	4.25a (0.56)	2.78 (0.48)	5.15a (0.87)	3.18a (0.42)

[a]Damaged by wild boars.
[b]Means in columns followed by the same letter(s) are not significantly different at $P \leq 0.05$ by LSD.
[c]Standard error.

Table V. Uptake of N, P, and K by maize and groundnut as influenced by crop-residue application

Treatment	First crop (Maize)	Second (Groundnut)	Third (Maize)	Fourth[a] (Groundnut)	Fifth (Maize)
			($kg\ ha^{-1}$)		
			Total N		
T1	50.3a[b] (3.19)[c]	253a (14.1)	57.3ab (4.29)	102 (12.8)	57.3b (12.1)
T2	55.9a (0.95)	268a (13.18)	47.2b (9.45)	109 (23.96)	54.3b (8.66)
T3	58.9a (11.9)	240a (14.9)	75.9a (10.1)	116 (16.4)	90.5a (16.3)
			Total P		
T1	6.24a (0.35)	23.0a (1.40)	9.40a (0.71)	7.39 (0.93)	7.33b (1.00)
T2	6.29a (0.40)	25.2a (0.50)	8.18a (1.47)	12.1 (3.11)	7.39b (0.70)
T3	11.7a (2.95)	23.9a (1.45)	11.6a (1.20)	15.4 (0.84)	12.1a (0.95)
			Total K		
T1	33.8b (4.36)	180a (20.0)	86.4b (4.56)	79.0 (11.9)	57.4b (11.6)
T2	33.3b (1.85)	148a (15.0)	51.9c (11.9)	58.7 (11.5)	44.0b (8.20)
T3	53.5a (7.05)	179a (18.7)	124a (11.6)	80.3 (5.95)	94.7a (20.8)

[a]Damaged by wild boars.
[b]Means in columns followed by the same letter are not significantly different at $P \leq 0.05$ by LSD.
[c]Standard error.

In all maize crops, K uptake was significantly increased by organic residues. In the first season, chicken manure significantly increased total K uptake over no manure by 58 to 61%. In the second maize crop, applications of crop residue (T1) and crop residues combined with chicken manure (T3) had significantly higher total K contents over the control (T2). In the fifth crop, total K in T3 plots was significantly higher than in T2 by 115%. For groundnut, application of crop residues or combined with chicken manure had no significant effect on K content. This is because almost all K present in the chicken manure is in the exchangeable form, with values ranging from 97 to 100% of the total K content [17]. Similar results were found before: application of 4 t ha^{-1} of millet straw over a 4-year period increased total K content of pearl millet by 65% over K in crops treated only with fertilizer [17].

3.2. Recovery of fertilizer N and first-maize residue N

Values for recovery of ^{15}N by the first and subsequent crops are presented in Fig. 2. In the first crop (maize), 19 to 22% of the applied ^{15}N (60 kg ha^{-1}) was recovered in aboveground plant parts. In the second crop (groundnut) total recovery of labelled N in the plant was lower than that of the first crop. Total ^{15}N was found to be 5.1 and 5.6% in the T1 and T2 plots, respectively.

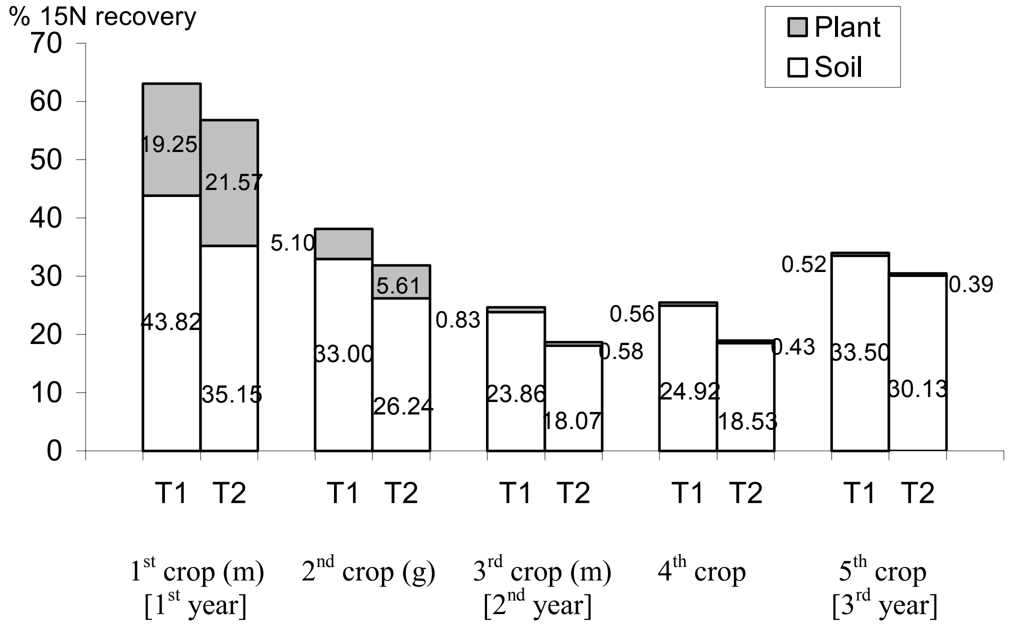

FIG. 2. Recovery of ^{15}N in the soil and plant.

Cumulative recoveries of ^{15}N (i.e. first and second crops) were 24% in T1 plots and 27% in control plots. In the third crop, total plant recovery in T1 was small (0.83%) but higher (albeit not significantly) compared to T2 (0.58%) (Fig. 2). In the fifth crop (maize) total N recovery was 0.52% in T1 and 0.90% in T2. It was observed that continuous incorporation of crop residues significantly improved total recovery over the control, by about 33%. In general, fertilizer use efficiency values in the second and subsequent crops were low and ranged from 0.52 to 5.1% in crop-residue-treated plots and 0.39 to 5.6% in the control plots.

After harvest of the first crop, 35 to 44% of the ^{15}N applied was retained in the top 50 cm of soil, of which 70 to 78% (average 75%) was in the 0- to 15-cm layer (Fig. 2). In general, recovery of the applied N in the soil after harvest of subsequent crops was greatly improved by incorporation of crop residues. Significant positive effects of crop residues on fertilizer N-use efficiency were observed in the 15- to 30-cm soil depth after the second and third crops in the rotation. At these depths, incorporation of crop residues increased N recovery, compared to residue-removal plots, by 91% after the second crop and by 65% after the third crop. The respective values in residue-treated plots for the crops listed above were 33, 24, 25, and 34%, respectively. Difference in N recovery between incorporation and complete removal was significant after harvest of the third crop only. From the second through the fifth crops, fertilizer-N recovery in residue-treated plots (T1) averaged 29% compared to 24% in plots from which residues were completely removed (T2). After the second, third, fourth and fifth crops in the cycle, incorporation of residues had increased N retention of the topsoil, over the control, by 12, 16, 23, and 18%, respectively. The fertilizer-N recovery (21%) observed in the first crop (maize) in this study was within 8.0 to 36% of other values reported in the tropics [18]. In the present study, low plant recoveries of ^{15}N could be explained in terms of rapid immobilization of NH_4 [19], the form in which the ^{15}N was applied. Low N recoveries after the second crop (5.1–5.6%) are consistent with results of Crozier et al. [20] who reported recoveries of ^{15}N of only 1 to 3% after the second crop. In the United Kingdom, slightly increased uptake of labelled N by winter wheat was reported in the presence of wheat straw [21]. Because the amount of microbial biomass C per unit organic C in the soil is greater in the topsoil, more recovery in the topsoil is generally found [22]. The residual value of the fertilizer N in control plots averaged across four seasons reported here (24%) was comparable to those found under humid conditions reported in another study [23]: below 20%.

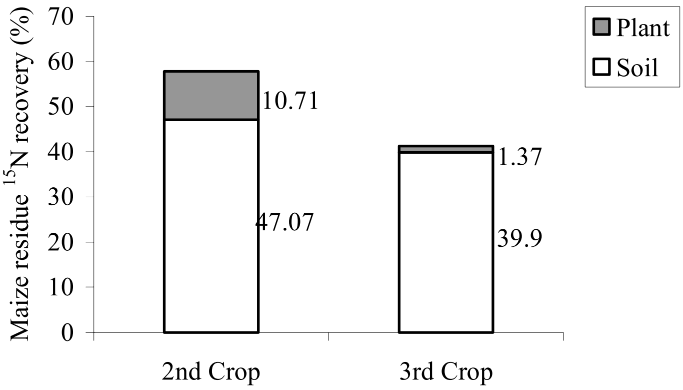

FIG. 3. Recovery of ^{15}N-labelled first maize residue in the soil and plant.

Recoveries of first-crop (maize) residual N in the soil-crop system (Fig. 3) after the fourth and fifth crops were low and may not be real values because of the low atom percent ^{15}N excess. The highest recovery of residue ^{15}N (11%) in the plant was observed in the second crop and decreased in subsequent crops. Most of the residual ^{15}N remained in the soil profile (0–50 cm) after harvesting the crops in the cycle. About 47% and 40% of the residue-N was found in the top 50 cm after harvest of the second and third crops, respectively. The recovery value in the second crop (11%) was within the range of cereal straw-N recovery by subsequent crop reported by others [21], i.e. between 5% and 20%. Recoveries of residue-N in the second and subsequent crops in this study (0.42–1.4%) were comparable to earlier findings [24]. In the present study, subsequent crops were sown 8 to 16 weeks after application of residues. During this period, losses of N were possibly occurred by volatilization and by leaching of mineralized N. Many field and laboratory studies under conditions of adequate humidity have reported ammonia volatilization from incorporated crop residues [25].

3.3. Effects of crop residues on soil properties

Table VI presents soil chemical properties after five crop cycles. Application of organic residues did not significantly affect soil pH, total N, or organic C. Available-P values in the 0- to 15-cm and 15- to 30-cm layers were significantly higher in T3 plots compared to T1 and T2. Applications of residues did not significantly increase available P in the soil. In the third crop, i.e. after incorporation of the first groundnut residue, similar observations were made with more available P accumulated in the manure-treated plots. In this crop, P content observed in the T3 treatment in the 15- to 30-cm and the 30- to 50-cm layers was significantly higher than in the control (T2) by 267% and 293%, respectively. Similarly, after four crops, contents of P in T3 of the 0- to 15-, 15- to 30- and 30-to 50-cm layers were significantly higher than in T2, by 192%, 146%, and 11%, respectively. Also, it was found that residues had no significant effect at any soil depth. At the end of the fifth crop, levels of P in chicken-manure (T3) plots in the 0- to 15- and 15- to 30-cm layers were significantly higher than in T2 by 236% and 114%, respectively. Applications of maize and groundnut residues after harvest and for two years caused no significant positive changes in available soil P. Exchangeable K was significantly higher than in the control (T2) in the 0- to 15- and 15- to 30-cm layers by 267 and 375%, respectively. Incorporation of crop residues had no significant effects on CEC whereas combining crop residues with chicken manure (T3) significantly ($P \leq 0.01$) increased it by 12% in the topsoil over T2. At sowing of the fifth crop (maize), SMN of the topsoil in T1 plots was not significantly different from that in T2, though it appeared to be slightly higher. However, in topsoil of T3 plots, SMN was significantly higher than the control (T2), by 78%. Absence of significant effects of residues on soil pH might be due to the lime applied before sowing the crops.

Table VI. Soil properties as influenced by four and five crop-residue applications

Treatment	pH (H_2O)	TN (%)	Org. C (%)	Avail. P ($\mu g\ g^{-1}$)	Exch. K (cmol(+) kg^{-1})	CEC (cmol(+) kg^{-1})	Total min'l N ($\mu g\ g^{-1}$)
				0–15 cm			
T1	6.22a[a] ±0.07[b]	0.11a ±0.01	1.39a ±0.09	40.3b ±4.00	0.21b ±0.03	7.03ab ±0.39	40.2b ±3.80
T2	6.30a ±0.07	0.11a ±0.01	1.34a ±0.04	45.2b ±12.57	0.09c ±0.02	6.64b ±0.36	34.1b ±2.10
T3	6.38a ±0.09	0.12a ±0.01	1.42a ±0.06	152a ±10.1	0.33a ±0.05	7.41a ±0.46	60.5a ±5.05
				15–30 cm			
T1	4.69a ±0.17	0.07a ±0.01	0.96a ±0.07	8.09b ±2.05	0.12a ±0.01	6.64a ±0.14	42.9a ±3.00
T2	5.05a ±0.13	0.08a ±0.00	0.99a ±0.04	14.2b ±1.59	0.04b ±0.00	6.56a ±0.45	32.9a ±4.90
T3	4.87a ±0.13	0.07a ±0.01	0.95a ±0.09	30.3a ±3.57	0.19a ±0.02	6.72a ±0.44	50.7a ±9.00
				30–50 cm			
T1	4.32a ±0.09	0.06a ±0.00	0.67a ±0.04	4.46a ±0.39	0.11a ±0.01	5.61a ±0.37	ND[c]
T2	4.71a ±0.13	0.06a ±0.00	0.79a ±0.01	9.63a ±1.65	0.09a ±0.01	5.84a ±0.69	ND
T3	4.47a ±0.03	0.06a ±0.00	0.68a ±0.01	11.57a ±3.66	0.13a ±0.01	5.38a ±0.37	ND

[a]Means in columns followed by the same letter are not significantly different at P ≤0.05 by LSD.
[b]Standard error.
[c]Not determined.

The content of soil organic C reported in this study remained almost unchanged for the five-crop cycle (Table VI). This is consistent with a study conducted under hot conditions that showed that in 12- and 14-year studies of incorporation of wheat residue, SOM changed very little [26]. In contrast, some studies have confirmed positive increases in organic matter with application of residues [27], indicating that decomposition of plant residues added to the soil is an important component in the turnover of organic C that depends on several conditions: plants, soil, management (e.g. soil tillage) and climate. Phosphorus levels in the soil determined in this study indicated that application of maize and groundnut residues for 2 years had no positive effects. The available P levels reported here are consistent with those determined in another study [17] in which there was no significant effect of incorporating millet straw for 4 years between control and residue-treated plots with or without fertilizer application. Higher exchangeable K in the T1 and T3 treatments was presumably caused by the additional K from residues and chicken manure. The percent increases in K content in the topsoil reported here (20–133%) in response to residue application are general similar to that observed in another study (87% in the 0–30-cm layer) [28]. Absence of significant changes in CEC after application of residues during the study period could be due to the rapid decomposition of organic matter during the rainy seasons. Therefore, longer-term, continuous applications of residues may be needed for significant increases in CEC. Similar results were observed in another study [17]: there were no significant effects on CEC after 4 years of incorporation of millet straw. Significantly higher SMN observed at sowing of the fifth crop was later (at harvest) correlated with significantly increased uptake of N by the fifth crop (maize), which was sown 2 weeks from application of the chicken manure compared to more than 3 weeks for the previous manure applications. Therefore, relatively little loss of N was expected. The lack of significant effects of residues on SMN after incorporation (T1) might be attributed to the longer fallow period (11–20 weeks) after harvest of the subsequent crops. In the humid tropics of Thailand, more than 50% of the N was lost from decomposing groundnut in the first 2 weeks after application [29]. This suggests that much of the easily released N from the residue had been lost via leaching or volatilization during the fallow period before it was recovered or that the remaining N was more resistant to decomposition.

The dry-matter weight values, C and N contents and C/N ratio of the sand-size SOM fraction [also called particulate organic matter (POM)] are presented in Table VII. Dry matter contents of POM in residue-treated plots (T1) or combined with chicken manure (T3) after the second and fourth crops were not statistically different from the control (T2), though they appeared to be slightly higher. Similarly, the C and N contents were also not significantly affected by residue application. Values for sodium iodide (density <1.8 g cm^{-3}) SOM light fractions (NAL), free and occluded, dry matter weight, N and C contents and C/N ratio of the topsoil determined after harvest of the fourth crop are presented in Table VIII. Whether crop residues were added or not, weights of free light organic matter fractions (NAL) were statistically similar between treatments. However, weight of the occluded SOM light fraction in T3 plots was significantly lower than in T2 by 59%. In general, the total dry weight of NAL ranged from 2.14 in T3 to 4.23 g kg^{-1} soil in T1, whereas the occluded fractions ranged from 0.34 in T3 to 0.83 g kg^{-1} soil in T1 and T2. Nitrogen content of NAL was not statistically affected by incorporation of crop residue (T1) or chicken manure (T3). It was found to range from 6.5 to 18.5 mg N kg^{-1} soil in the free and from 1.3 to 5.8 mg N kg^{-1} soil in the occluded fractions. Similarly, C/N ratio was not significantly affected and ranged from 15 to 19 in the free fractions and from 5 to 10 in the occluded fractions. The N and C/N ratio values of the whole soil were 0.11 and 13, respectively. Therefore, it can be observed that the C/N ratio of the light fractions (free organic matter) was greater than the C/N ratio of the whole soil. Absence of significant effects on soil physical properties indicates that, in the humid tropics, there is insignificant build-up of SOM in the short term due to rapid decomposition. However, SOM may accumulate slowly over the long term.

Table VII. Contents of the soil organic matter sand-size fraction, N, and C, and C/N ratio after the second and fourth crops, as influenced by crop-residue application

Treatment	Weight (g kg^{-1}soil)	N (mg kg^{-1}soil)	C (g kg^{-1}soil)	C/N
		After the second crop		
T1	33.4a[a]	133a	3.07a	22.8a
	(15.9)[b]	(60)	(1.6)	(3.3)
T2	22.6a	72a	1.41a	19.9a
	(6.3)	(20)	(0.40)	(5.7)
T3	45.8a	94a	1.45a	17.3a
	(3.6)	(40)	(0.30)	(6.5)
		After the fourth crop		
T1	28.1a[a]	115a	2.24a	18.2a
	(8.3)[b]	(60)	(1.5)	(3.9)
T2	18.7a	98a	2.20 a	22.4a
	(9.9)	(20)	(0.80)	(7.1)
T3	24.6a	82 a	1.75a	21.5a
	(7.4)	(10)	(0.40)	(5.6)

[a]Means in columns followed by the same letter(s) are not significantly different at P ≤0.05 by LSD. [b]Standard error.

Table VIII. Light fractions (NAL) of organic matter in the topsoil after four cropping seasons

Treatment	Weight ($g\ kg^{-1}$ soil)	N ($mg\ kg^{-1}$ soil)	C ($mg\ kg^{-1}$ soil)	C/N
		Free		
T1	4.23a[a] (1.43)[b]	18.5a (20)	358a (37)	16.9a (7.6)
T2	3.39a (1.13)	12.9a (10)	322a (32)	19.4a (10.4)
T3	2.14a (0.27)	6.5a (0.0)	106a (70)	15.4a (5.9)
		Occluded		
T1	0.83a (0.14)	1.3a (0.0)	10.6a (1.0)	7.7a (2.6)
T2	0.83a (0.14)	1.6a (0.0)	14.9a (0.0)	10.4a (4.4)
T3	0.34b (0.03)	5.8a (0.0)	3.3a (0.0)	5.4a (1.1)

[a]Means in columns followed by the same letter are not significantly different at $P \leq 0.05$ by LSD.
[b]Standard error.

Low C/N ratios of POM indicate that decomposition was accelerated under tropical conditions due to higher temperature during the rainy season. Carbon mineralization is known to be maximized between 25 and 45°C [30]. Soil temperature at the depth of crop-residue incorporation (0–20 cm) during the study period ranged between 26 and 31°C, which indicates that decomposition would be rapid. Accumulation of the POM fractions in the smaller soil particles is in line with the results of another study [27] that showed that decomposing plant residues rapidly accumulated in the fine soil fractions. Earlier work [31] showed that most plant-residue components decompose within 1 year of their incorporation. Light-fraction SOM levels reported in this study (2.48–5.05 $g\ kg^{-1}$) compared closely (1.9–4.9 $g\ kg^{-1}$) with those obtained with this method [32] in a long-term rotation in Canada and also with the 2.2 $g\ kg^{-1}$ soil value for a tropical soil under a maize-legume system [33]. In addition, the weight of NAL fractions reported from the sandy clay loam in this study (0.25–0.51% of the whole soil weight) is similar to the 0.1 to 0.4% SOM light fraction in sandy German soils [Leuschner et al. in 34]. Nitrogen content of NAL was not significantly affected by incorporation of crop residues. The C/N ratios of NAL reported here (15–19) are comparable to those (12–21) reported by other workers [35] for the tropics of Costa Rica. However, these values are lower than some (19–32) reported for a long-term rotation established in Canada [36]. This could be attributed to variations in environmental factors, such as moisture and temperature, which strongly influence decomposition rates. Significantly lower C and N contents of SOM (occluded) in the density-fractionation method reported in T3 plots indicate that the application of chicken manure enhanced decomposition of organic materials through stimulation of the soil micro-organisms.

3.4. Decomposition of maize residues and N uptake by subsequent groundnut

There was rapid loss of DMW of maize residue within 2 weeks of application; during this period, residue in T3 lost significantly more DMW (39%) than in T1 (29%) (Fig. 4a). It was also observed that 50% loss occurred after 7.2 and 7.6 weeks for T1 and T3, respectively. At the end of 12 weeks, DMW of the decomposed residue in T1 (26%) was not significantly different from that remaining in T3 (22%). The non-linear regression shows that decomposition of maize residues in T1 and T3 are best described using the single exponential model

$$W_t=W_o e^{-kt}$$

where

W_o is the original amount of material applied,
W_t is the proportion of the initial dry matter remaining after a period of time t in weeks,
k is the rate constant [1].

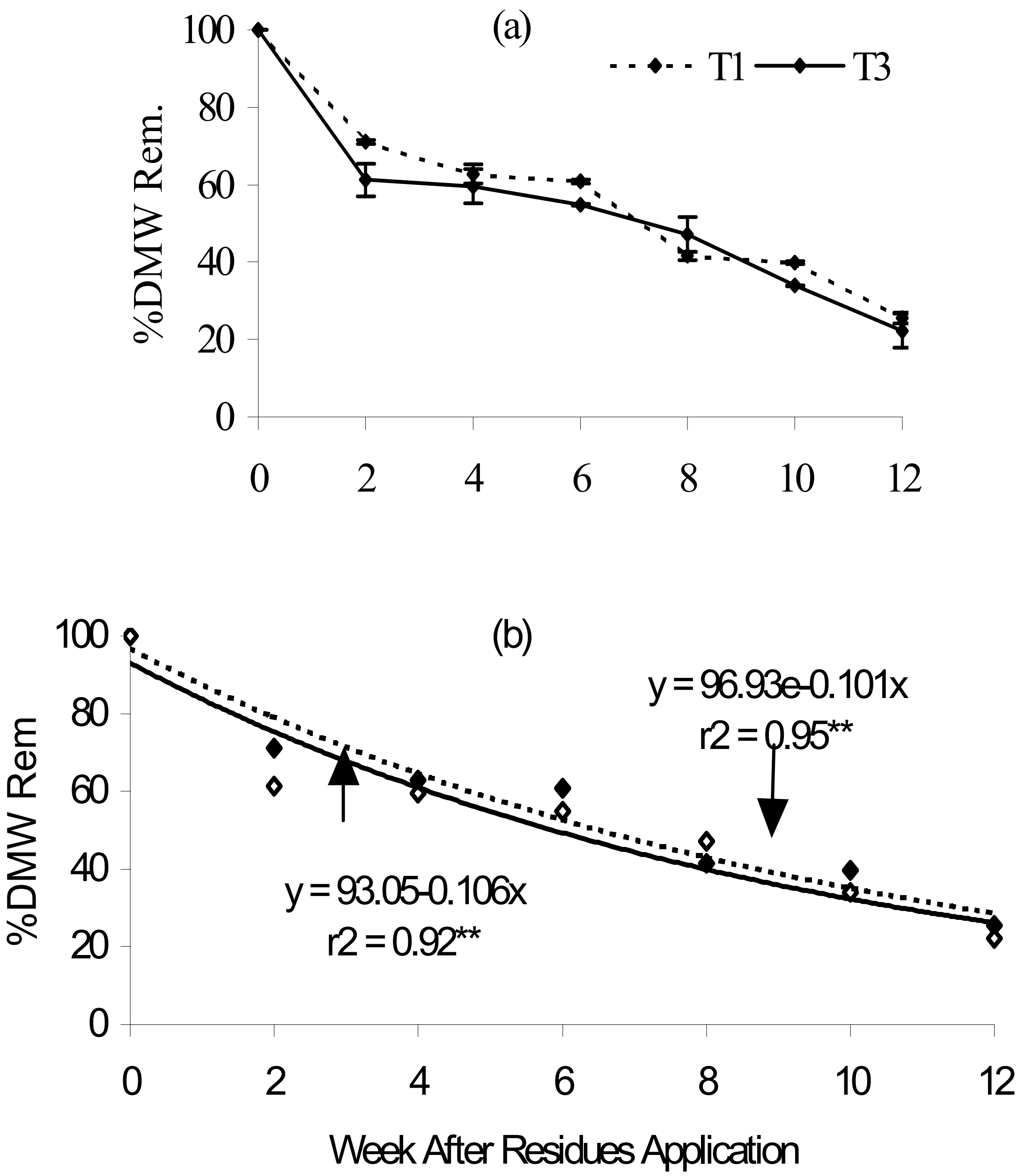

FIG. 4. Actual change of %DMW remaining of maize residue during the fallow period of 12 weeks (a) and non-linear decomposition rate curves (b). Bars represent standard errors.

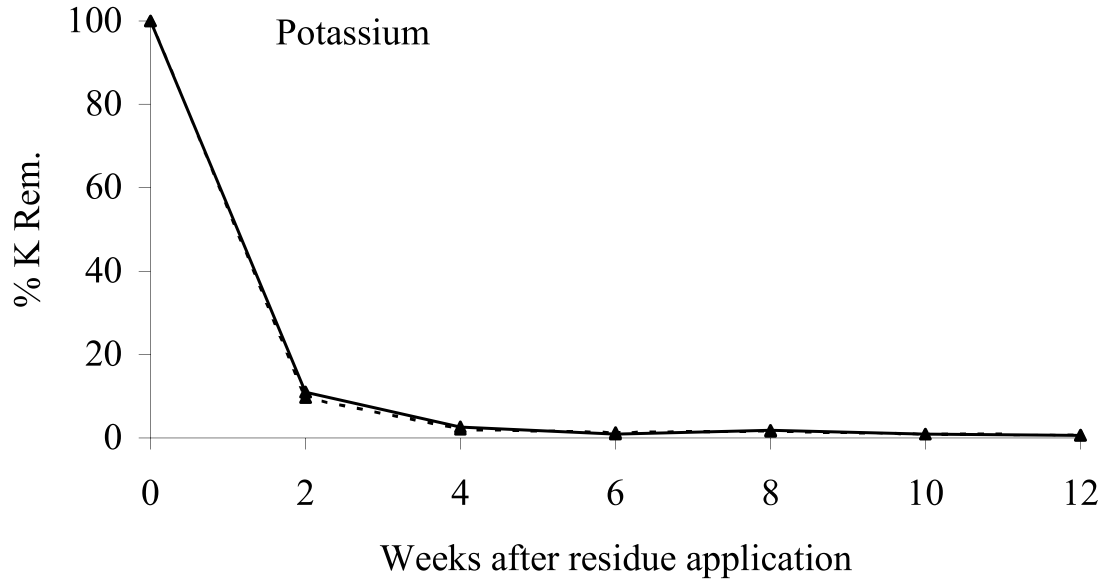

FIG. 5. Fraction of K remaining during decomposition of maize residues (solid line = T1, broken line = T3)

The decomposition or DMW-loss rate constants (k) in T1 and T3 were 0.101 week^{-1} and 0.106 week^{-1}, respectively (Fig. 4b). Potassium was lost more rapidly than the other nutrients and did not follow an exponential pattern (Fig. 5). This indicates that K was actively leached, as it was not a structural component of the tissue. After 2 weeks, only about 10% of the initial K remained in the decomposing tissue in T1 and T3, and it was not correlated to weight loss.

Thirty and 40% of initial-content C was lost from the residues in T1 and T3 after 2 weeks, whilst 50% loss occurred at 6.0 and 6.5 weeks after residue application (Fig. 6a). At the end of 12 weeks, only 18 to 20% remained. The patterns of C release as well as N were best fitted to the same exponential model as decomposition or DMW. Carbon-release rates, k, were 0.119 and 0.134 week^{-1} (Fig. 6a). Nitrogen release was more rapid in the first 2 weeks. After 2 weeks, residue N remaining in treatment T3 (50%) was significantly less than that in T1 (63%) (Fig. 6b).

In the presence of chicken manure, 50% of the initial N was released after 2 weeks, whereas in its absence, 50% was released after 7.5 weeks. At the end of the 12-week fallow period, 21 to 28% of the initial N content remained in the residues in T1 and T3. In general, the pattern of N release was best described by the single exponential model with k = 0.082 and 0.101 week^{-1} for T1 and T3, respectively. The rate of N release was similar to the rate of DMW loss, having similar k values. The ^{15}N-tracing technique measured in terms of N recovery in the soil showed that after 2 weeks of incorporation of the maize residues, N recovery in the soil was 63% and 49% in T1 and T3, respectively (Fig. 7). After 10 weeks, these increased to 74 and 52%, respectively. However, late in the season (after 21 weeks), recovery increased to 68% in T1 and decreased to 43% in T3. Figure 6c shows that, initially, the release of P was rapid in both treatments (45% and 41% of the initial content remained after 2 weeks for T1 and T3, respectively). After 12 weeks, the contents were 27% and 29% for T1 and T3, respectively. In general, release of P was best fitted to the polynomial model (Fig. 6c).

Total SMN in the topsoil (0–20 cm) after residue application is shown in Fig. 8 (data for the 20–40-cm layer are not shown). At week 4, the TSMN concentrations in the topsoil were low in T1 and T3, and higher in T2. This could be attributed to immobilization of the soil mineral N. Total SMN increased reaching peak values at week 8 (65.5, 62.4, and 54.3 µg N g^{-1} for T1, T2, and T3, respectively), with T3 significantly lower in N than T1 and T2 by 17 and 13%, respectively. A decrease in SMN was observed between weeks 8 and 18 then it was observed to increase. At almost all sampling times, NO_3^--N was found to be in greater concentration than NH_4^+-N. Residue incorporation in T1 and T3 resulted in slightly higher fresh pod yields than in the control, T2 (5.10, 5.17, and 4.89 t ha^{-1}, respectively), although differences between the were insignificant.

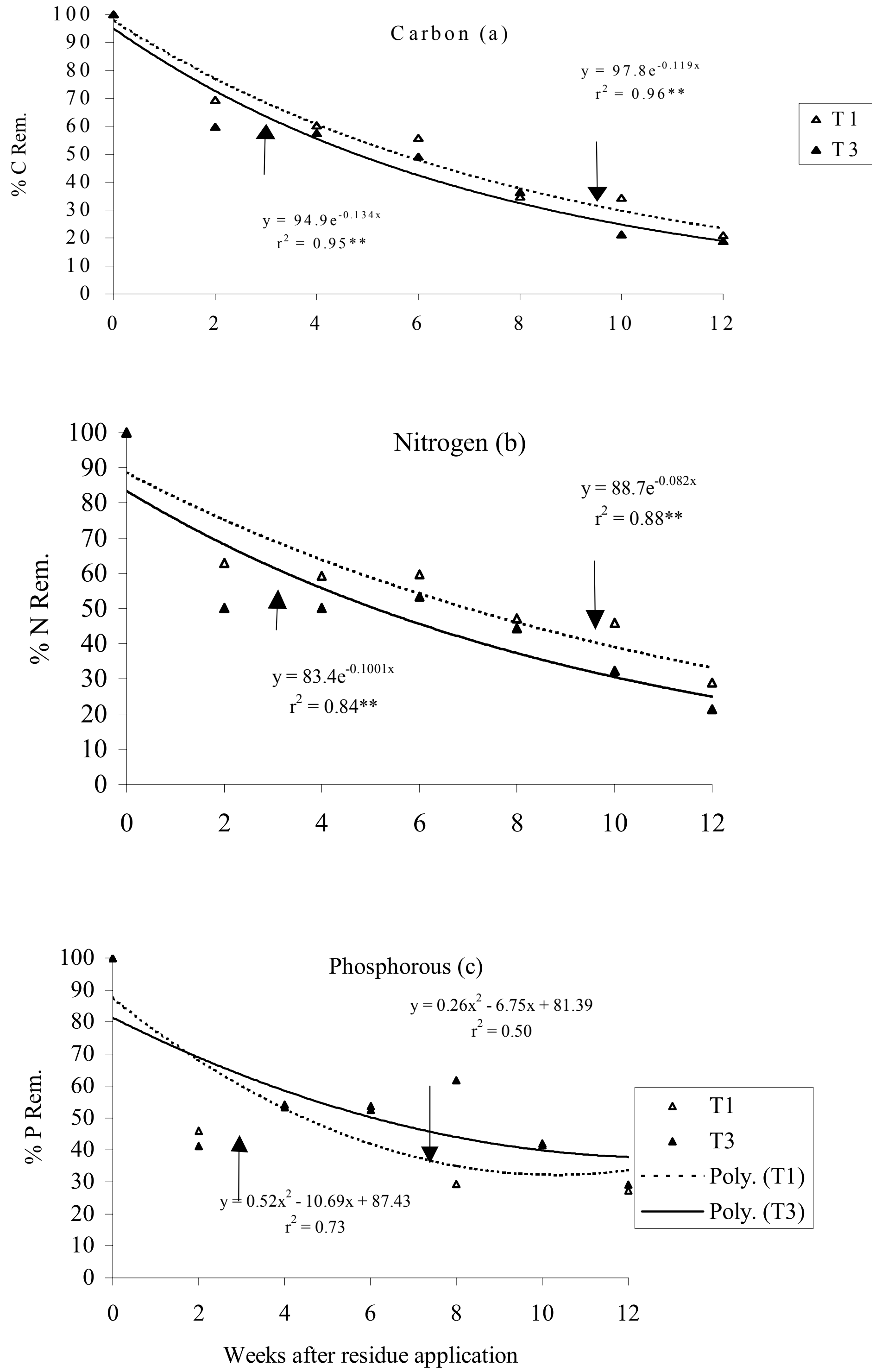

FIG. 6. Non-linear decomposition rate curves describing element release.

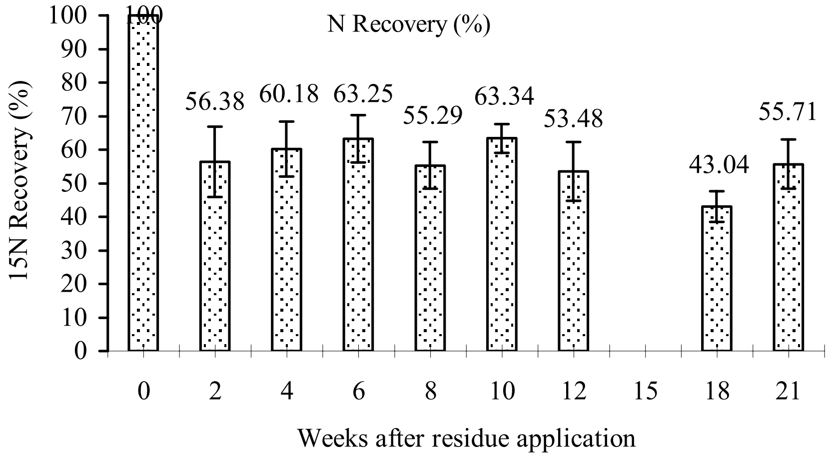

FIG. 7. Maize residue-N recovery (%) in the soil during decomposition.

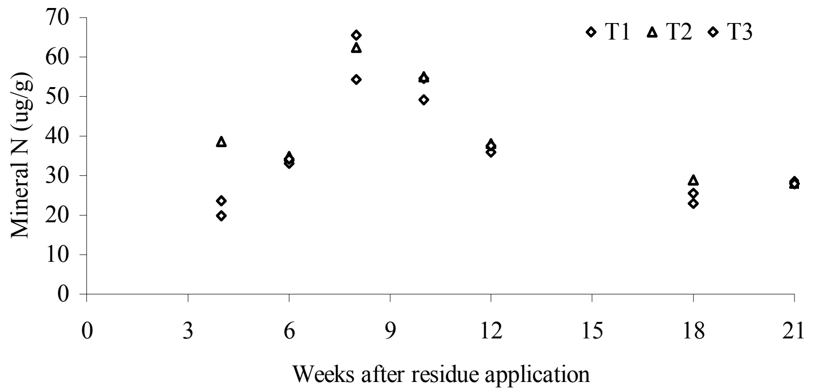

FIG. 8. Total soil mineral N ($\mu g\ N\ g^{-1}$) in the topsoil during decomposition of maize residues.

Figure 9 shows that the period of most active plant growth and N uptake was from 5 to 9 weeks after sowing. At harvest, N contents of the haulms and pods in residue-treated plots (T1 and T3) were higher than in plots without residue (316, 244, and 286 kg ha^{-1} for T1, T2, and T3, respectively), though statistically not significant.

The rapid loss of mass during the first 2 weeks after application of the maize residues could be attributed to the removal of water-soluble materials by rainfall. The significantly more rapid decomposition of chicken manure could be attributed to increased microbial activity resulting from higher pH and more available N. Increased of microbial biomass N with addition of chicken manure has been observed elsewhere [37]. The decomposition or DMW loss rate constants (k) in T1 (0.101 $week^{-1}$) and T3 (0.106 $week^{-1}$) are consistent with that reported for the tropical climate of Kenya [38]. The rate of N release was similar to the rate of DMW loss, having similar k values. Nitrogen release from prunings of legume hedgerows (C/N 11–20) has been reported to follow the order of mass loss [39]. The exponential model failed to give good fit with P release. However, although the exponential model is widely used to describe decomposition and nutrient-release patterns, prediction of decomposition rates using a certain model is not necessarily universally applicable. The rapid loss of K supports the theory that K availability from organic materials is due to non-biological processes, such as leaching of residue due to irrigation or rainfall. Generally, the pattern of nutrient release observed in this study was in the order of K > N = P > Mg > Ca. This pattern is consistent with that reported in another study [40].

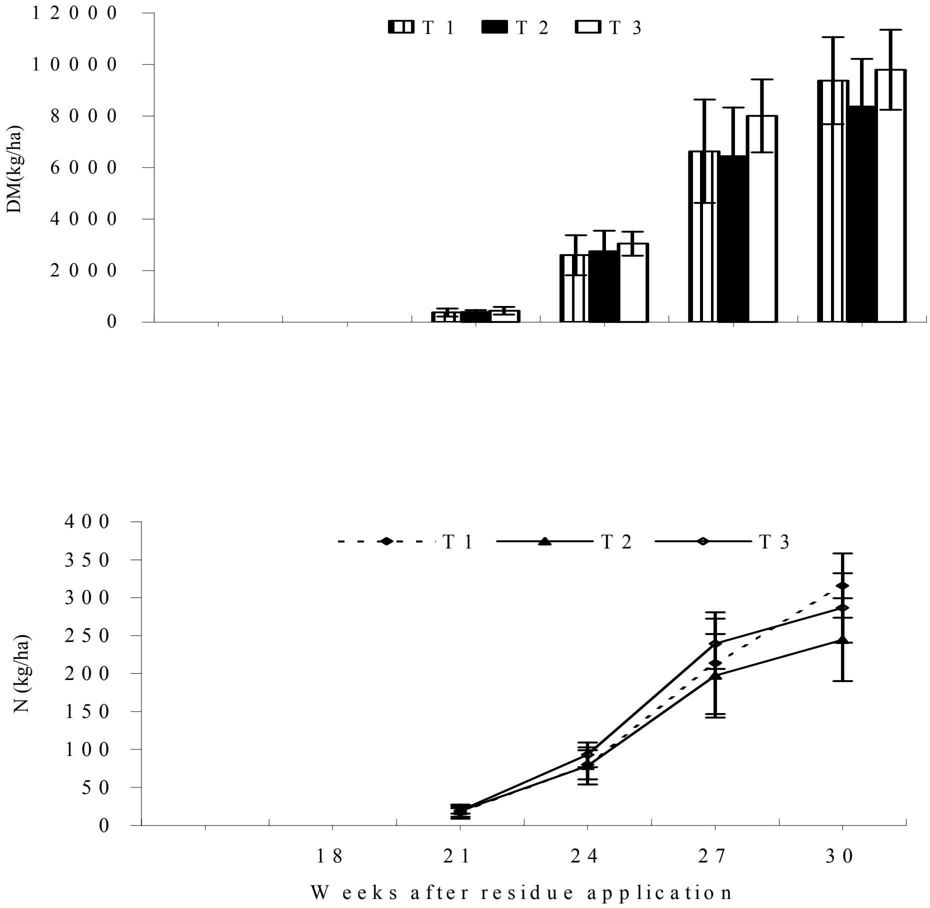

FIG. 9. Dry matter accumulation (upper) and N uptake (lower) (kg ha^{-1}) of groundnut. Bars represent standard errors.

It is postulated that the amount of biomass produced during the utilization of the soluble C fraction from the residues contributed to the immobilization of N in T3 after 8 weeks, despite the additional N in the chicken manure. In another study, when N was added during wheat-straw decomposition, there was more N immobilization [41]. In addition, microbial biomass may function as a sink for mineral N (immobilization) in phases of increased C supply. The lower values obtained after residue application could be attributed to immobilization of N. Nitrogen immobilization following residue application is widely documented [42]. Adding material of "lower quality" (high C/N ratio, high lignin and/or polyphenol levels) will decrease N mineralization. This effect has been observed as early as 2 to 8 weeks after incorporation [43]. The decrease in mineral N between 8 and 18 weeks might be attributed to the leaching of NO_3^- due to high rainfall reported during this period (339 mm). These results are consistent with others [44]. The decrease in rainfall at the end of the incubation period was accompanied with slight net N mineralization. These findings are in agreement with the statement that "N mineralization would be expected to be favoured by dry conditions over immobilization because microbial growth efficiency decreases and a lower proportion of N consumed by microbes is sequestered in the biomass" [45]. The net N mineralization at the end of the period may also be due to the late N mineralization. Similar results were reported from incubation experiments: the greater the immobilization of non-stover N during the initial stages of maize-stover decomposition (first 20 days), the more stover-N became available (mineralized) later in the experiment (after 40 days) [46]. Incorporation of residues appeared to result in slight increases in pod fresh weights in T1 and T3. Beneficial effects of groundnut-residue application have also been reported [32]. Moreover, millet straw was found to increase total dry matter and N accumulation in groundnut by 83% and 100%, respectively [28]. As observed from the residue decomposition, TSMN, and groundnut N-uptake results, groundnut should be sown between 4 and 8 weeks after maize residue application to provide optimal synchrony of crop uptake with residue-N release.

4. CONCLUSIONS

It could be concluded that in the humid tropics, unless the fallow period is short, i.e. 4 to 6 weeks, application of crop residues after harvest would not benefit the subsequent crop significantly because of rapid decomposition and release and loss of nutrients.

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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.

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

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).

$$Nc_{2,j} = \sum_{i=1}^{j} N_{2,i} \tag{2}$$

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).

$$N_{3,j} = N_{1,j} + Nc_{2,j} \tag{3}$$

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.

$$Nl_{3,j} = 100 - N_{3,j} \tag{4}$$

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

Nk,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.

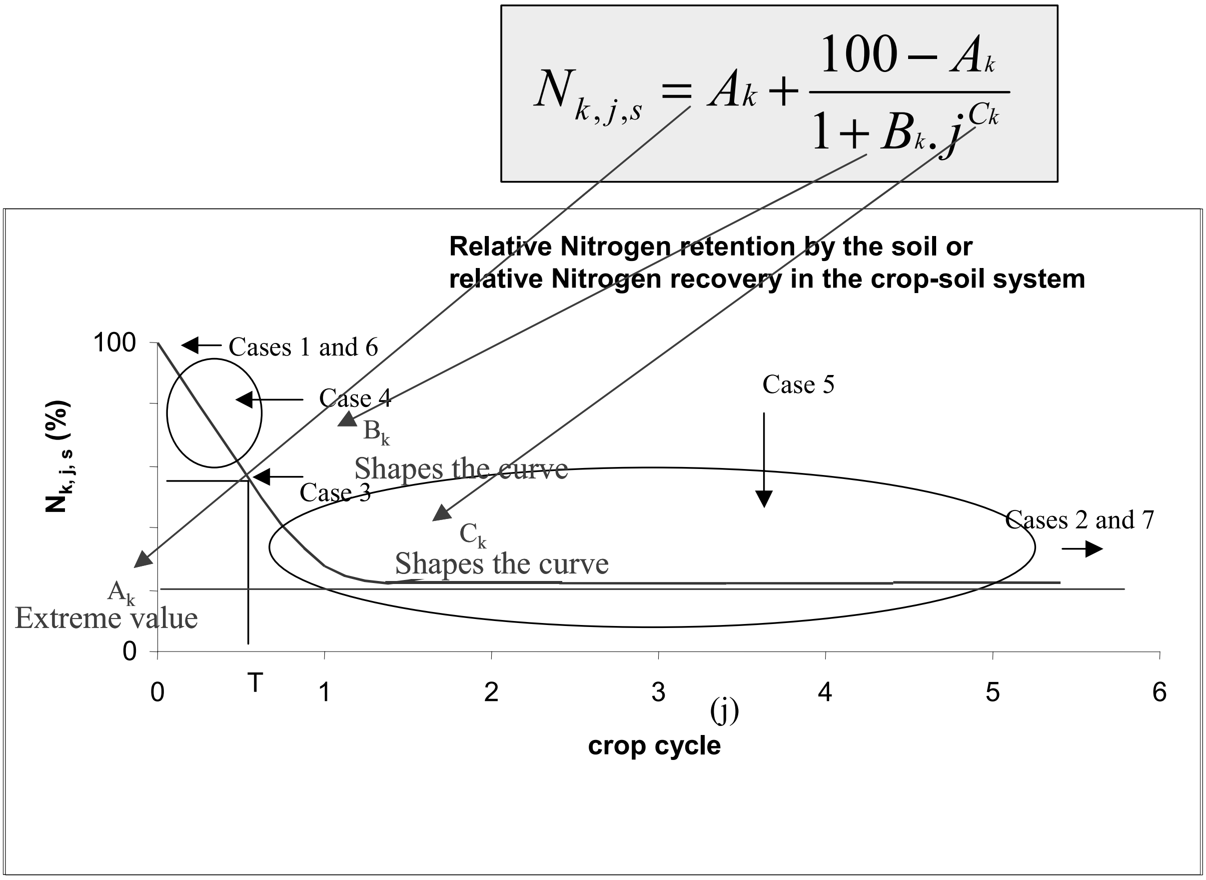

FIG. 1. Performance of Eq. 5, designed to represent the temporal variation of relative N retention in the soil and relative N retention in the crop-soil system; Eq. 5 satisfies all hypotheses (cases 1 to 7).

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

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

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.

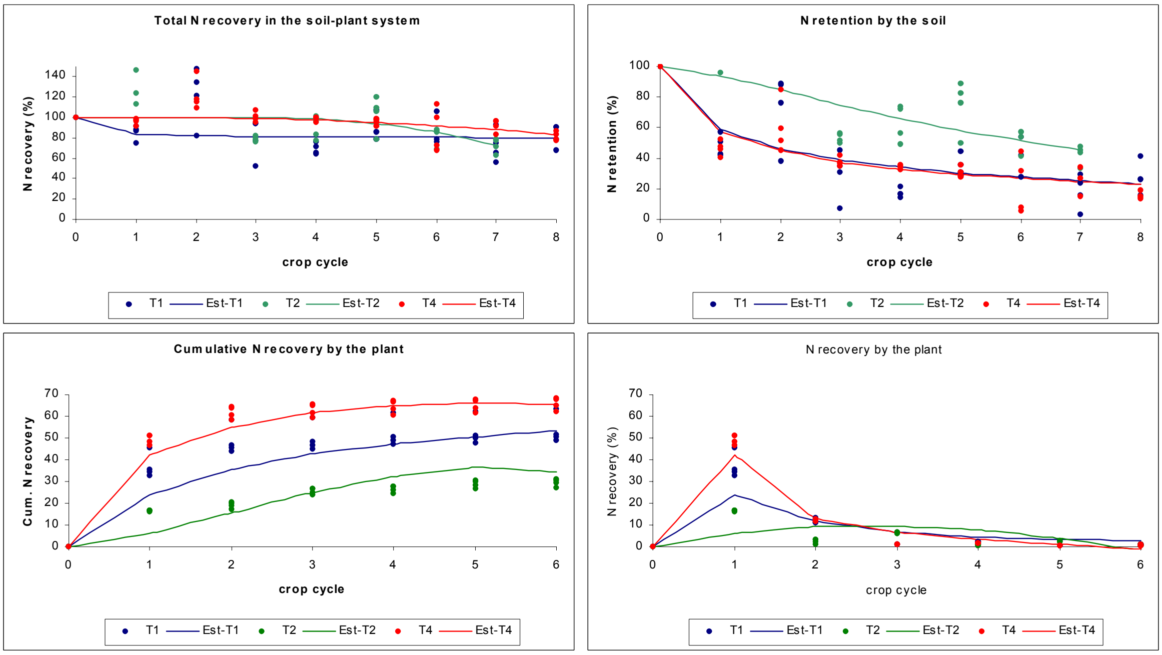

FIG. 2. Bangladesh: Fate of fertilizer N in a wheat-rice rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four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

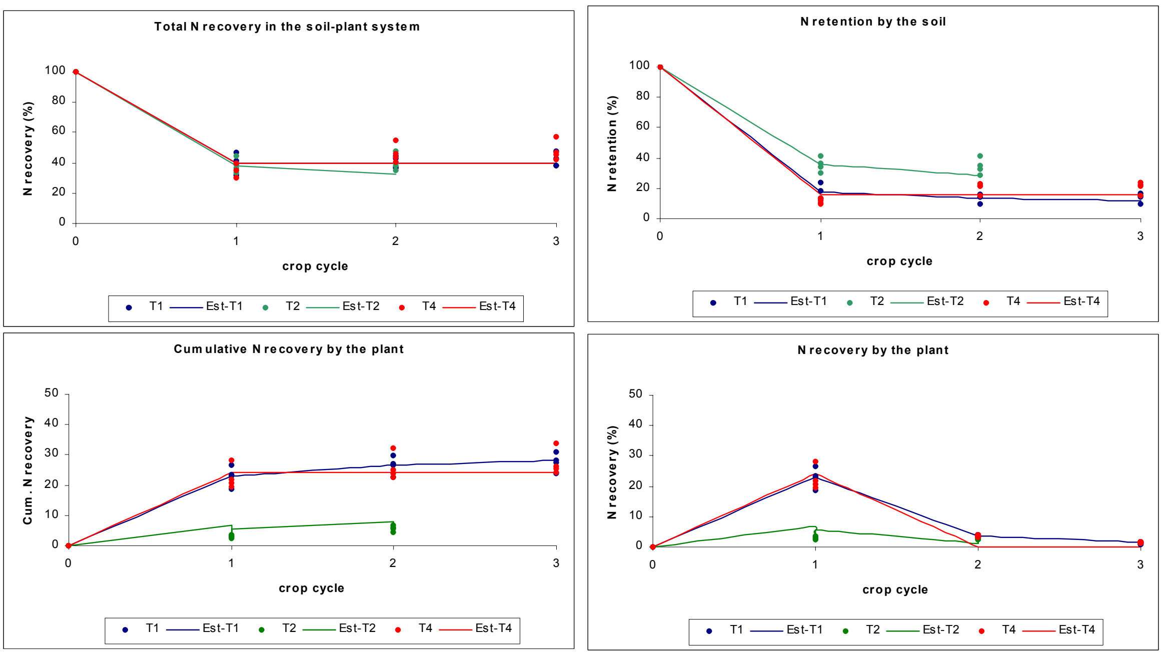

FIG. 3. Brazil: Fate of fertilizer N in a sugarcane monoculture. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four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

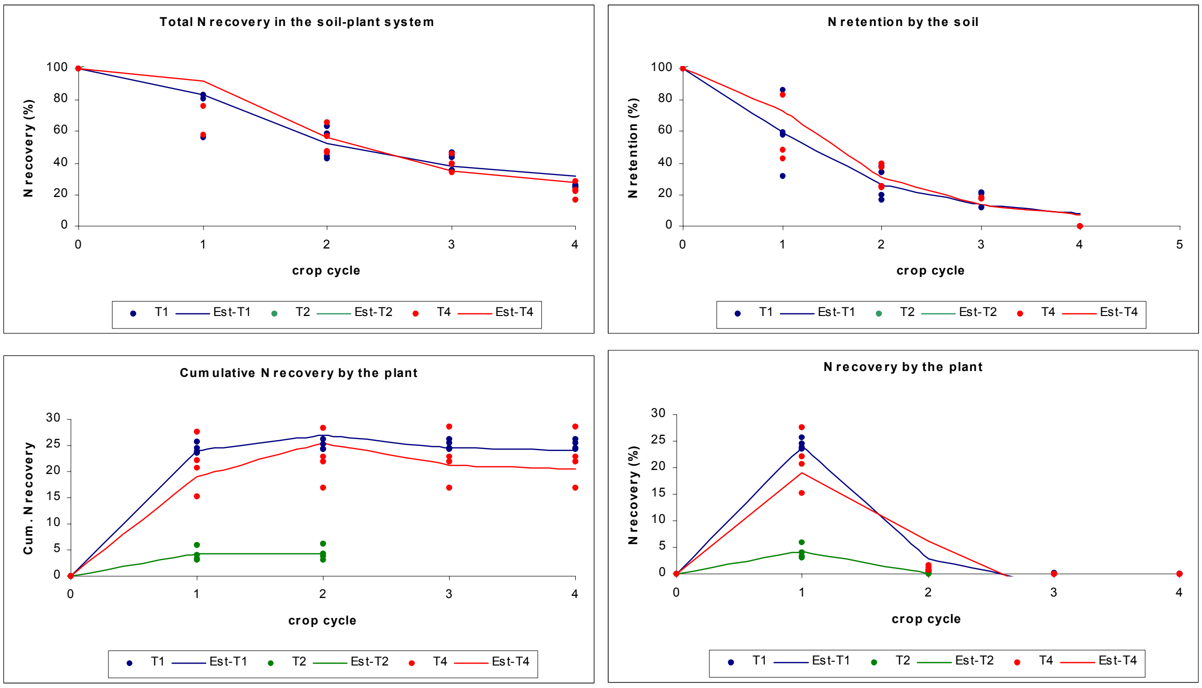

FIG. 4. Chile: Fate of fertilizer N in a maize-wheat-common bean-barley (or maize-wheat-red clover-red clover for T2 and T4) rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer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

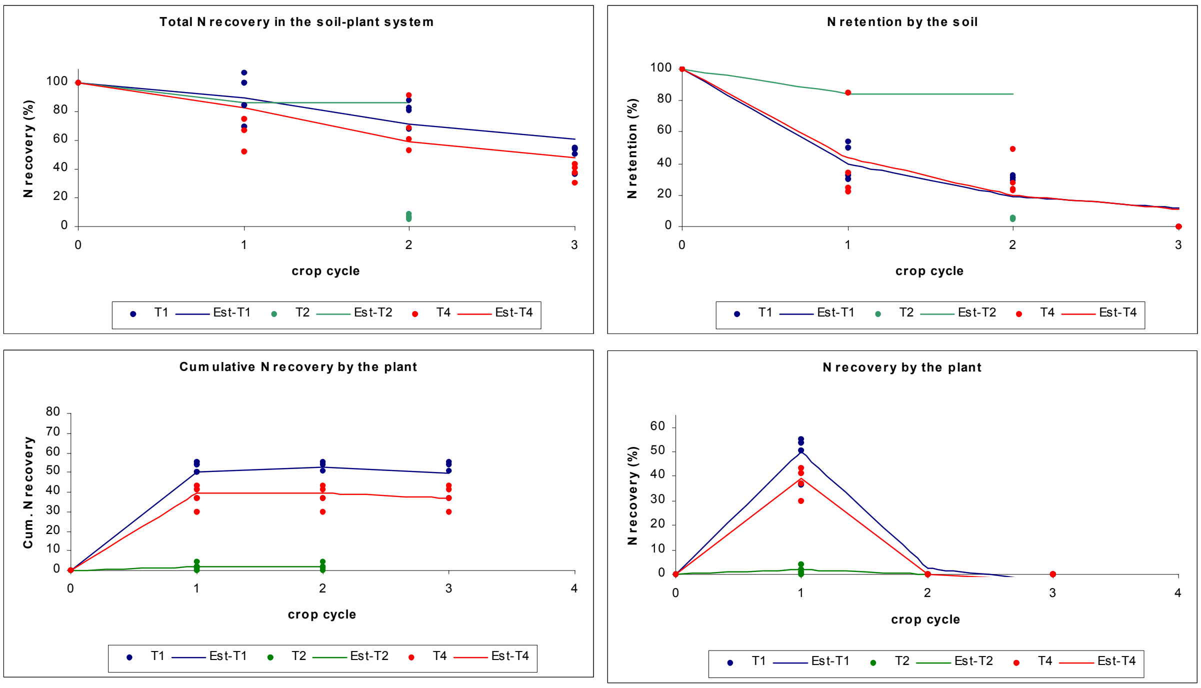

FIG. 5. Chile: Fate of fertilizer N in a maize-wheat-common bean-barley rotation (or maize-wheat-red clover-red clover for T4). T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added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

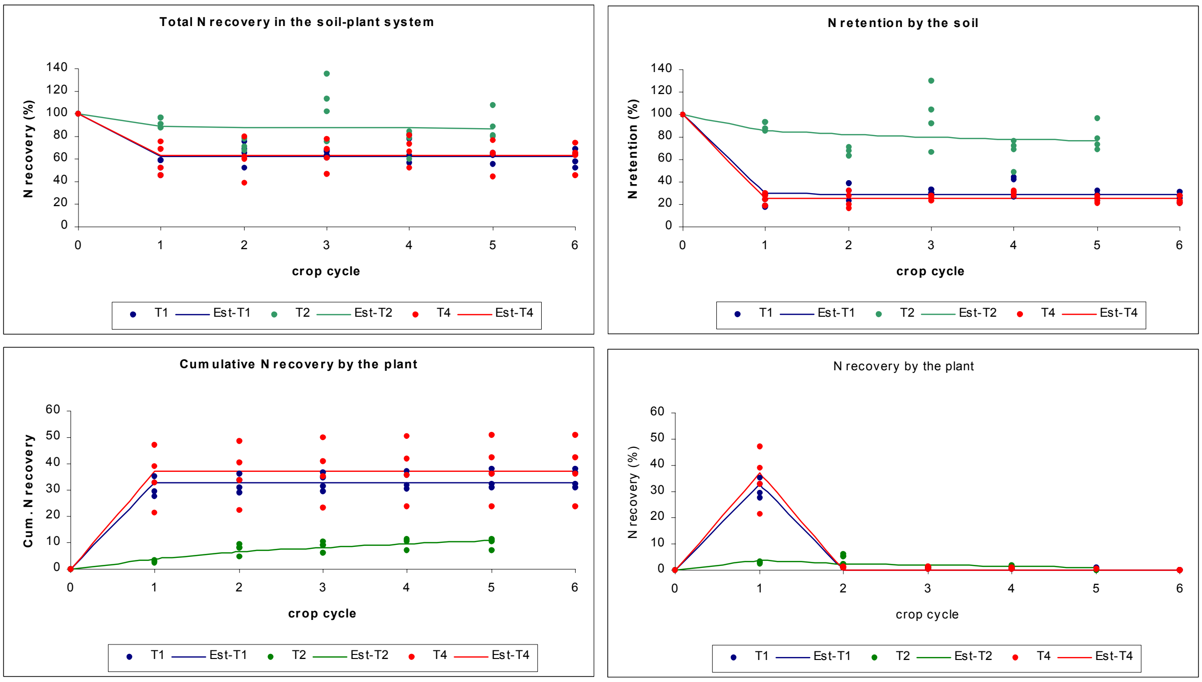

FIG. 6. China: Fate of fertilizer N in a rice-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four replicates,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

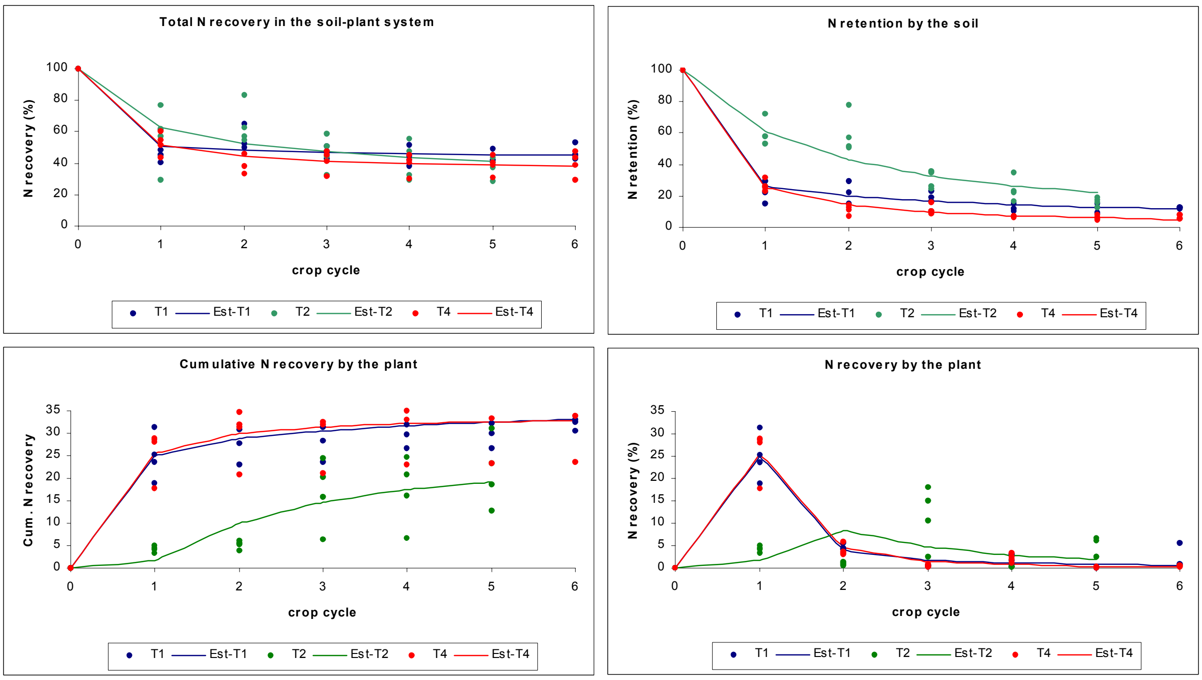

FIG. 7. Egypt: Fate of fertilizer N in a groundnut-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four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

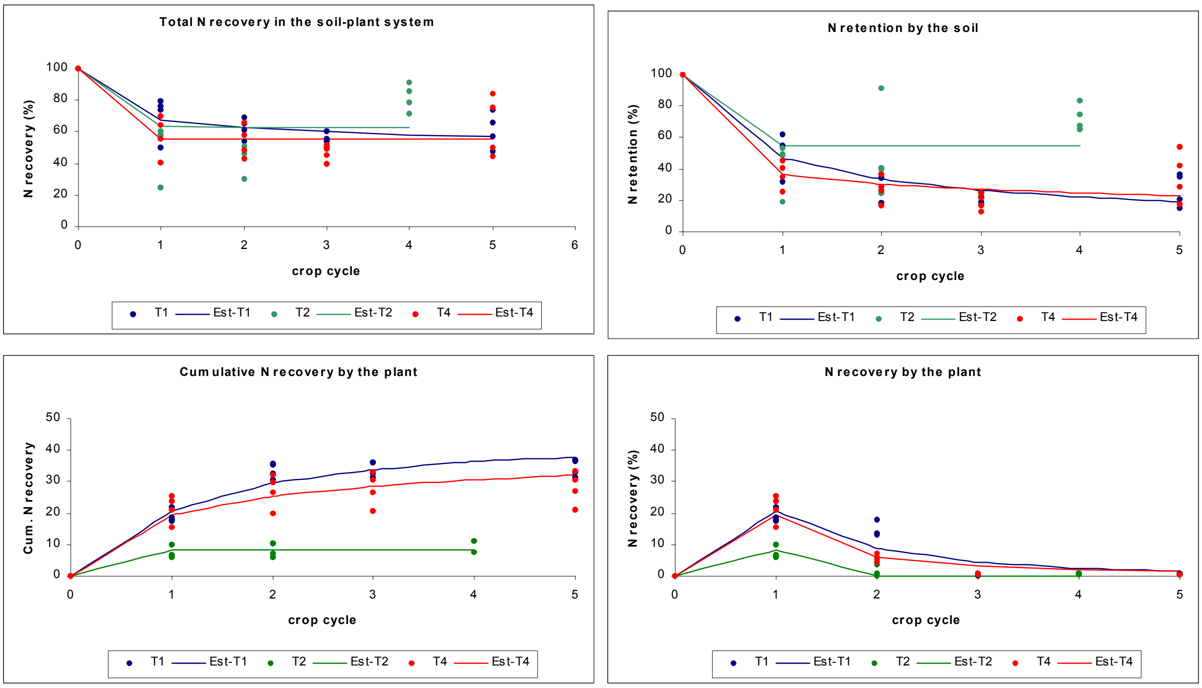

FIG. 8. Malaysia: Fate of fertilizer N in a maize-groundnut rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for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

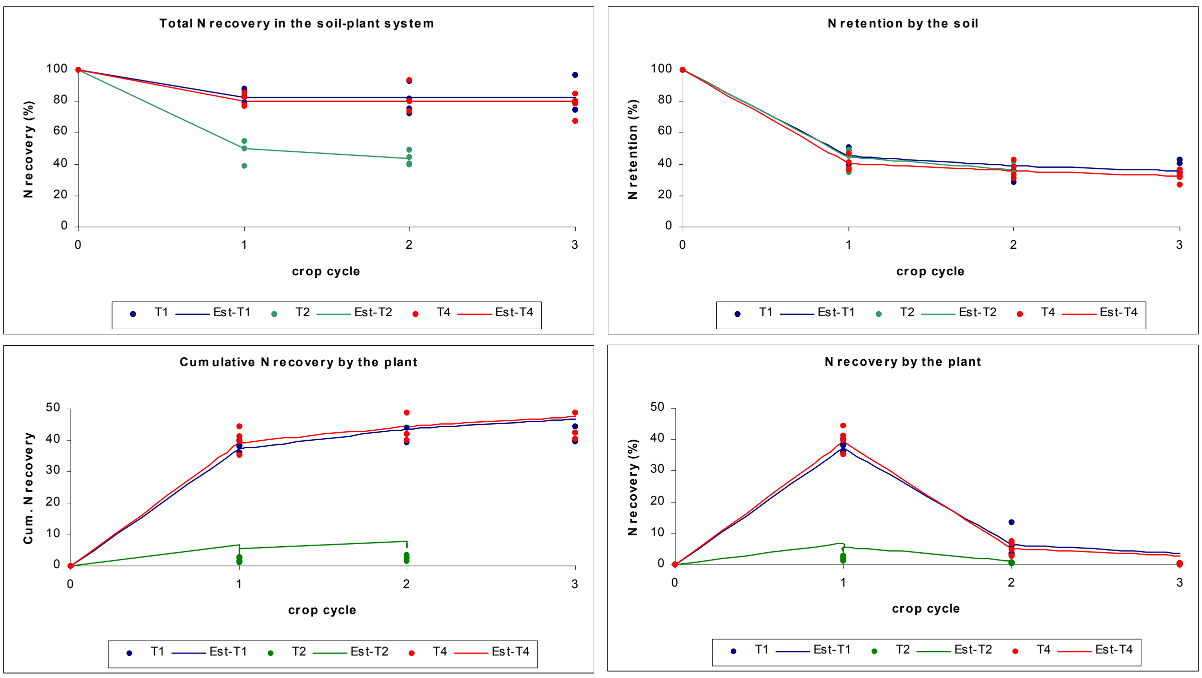

FIG. 9. Morocco: Fate of fertilizer N in a faba bean-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for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

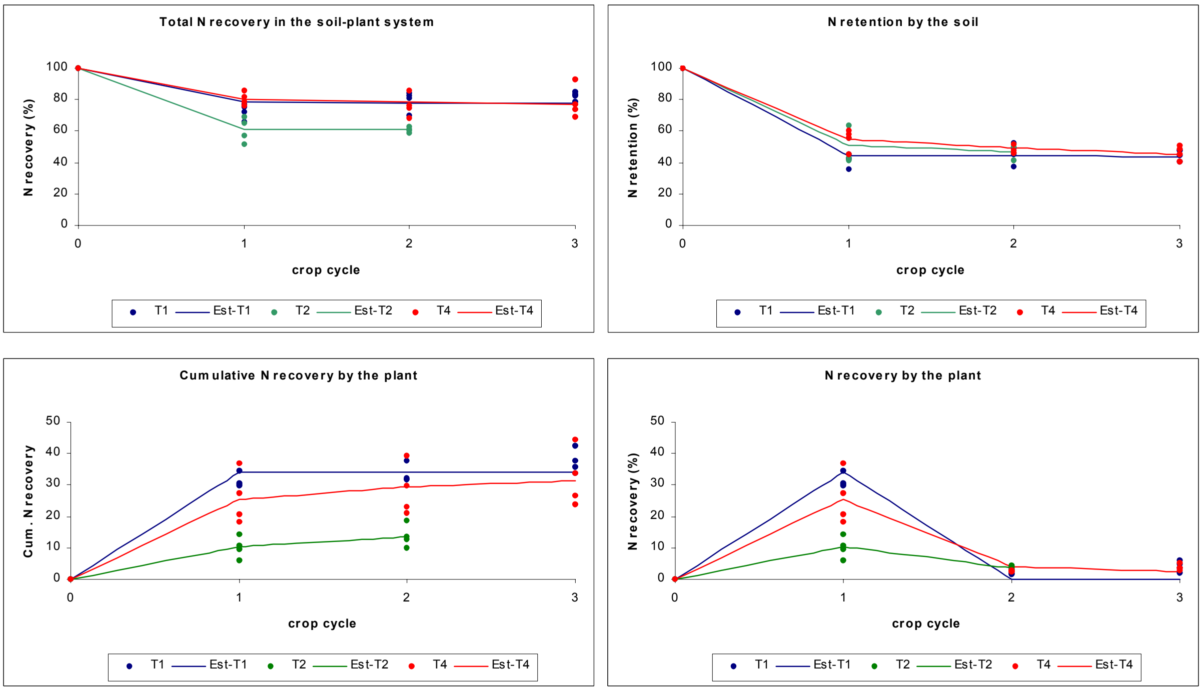

FIG. 10. Morocco: Fate of fertilizer N in a sunflower-wheat rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for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

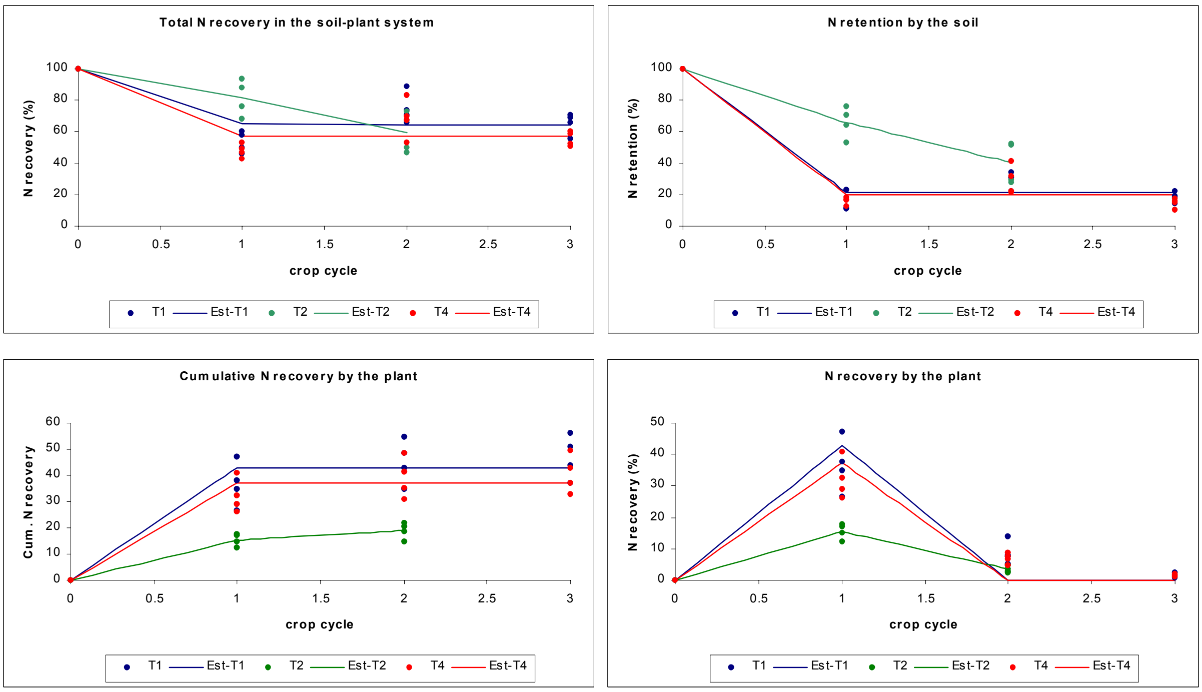

FIG. 11. Morocco: Fate of fertilizer N in a wheat monoculture. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for four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

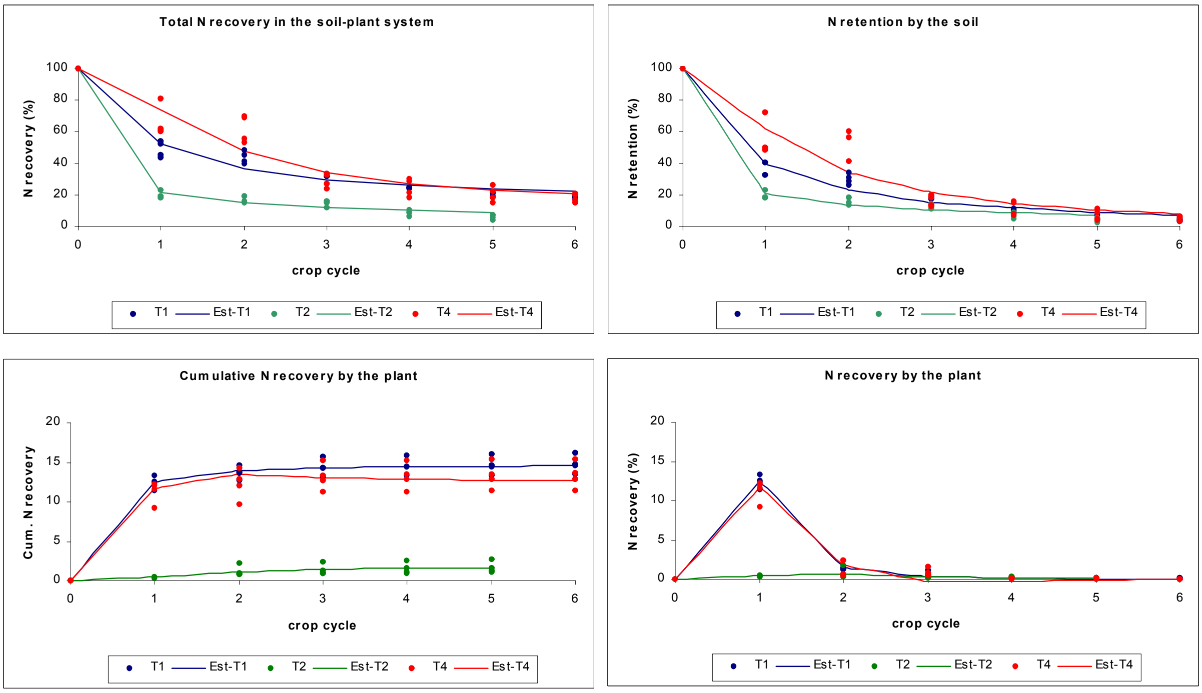

FIG. 12. Sri Lanka: Fate of fertilizer N in a mung bean-maize rotation, starting in the dry season. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points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

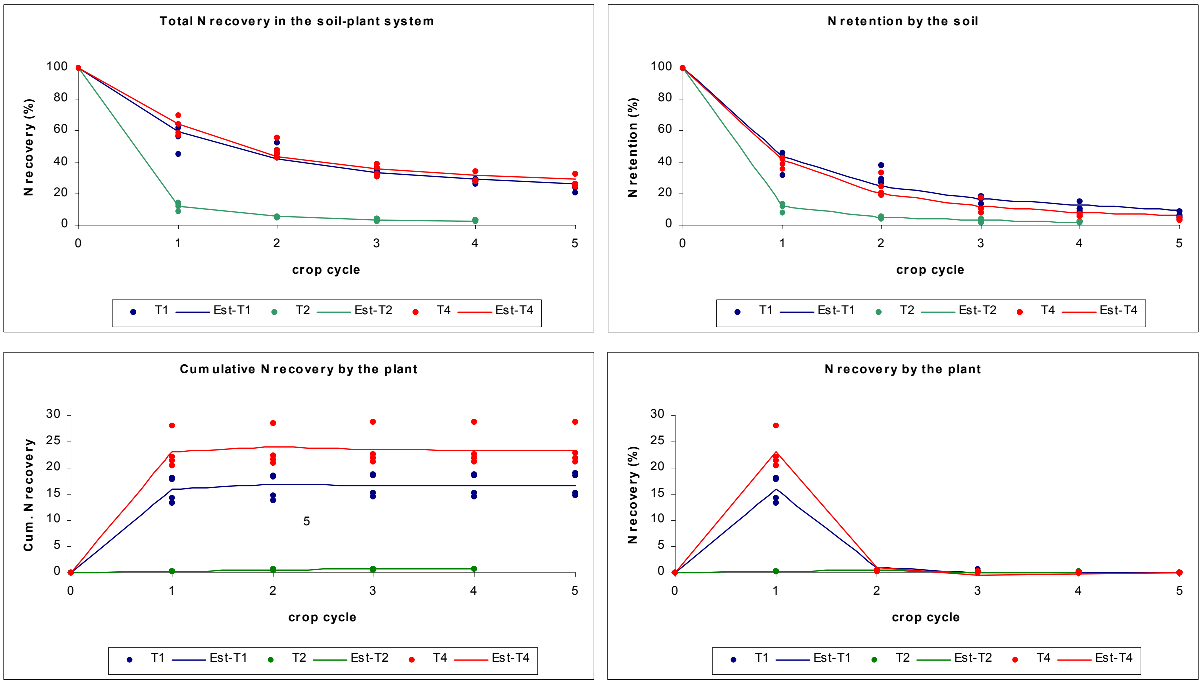

FIG. 13. Sri Lanka: Fate of fertilizer N in a mung bean-maize rotation, starting in the wet season. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points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

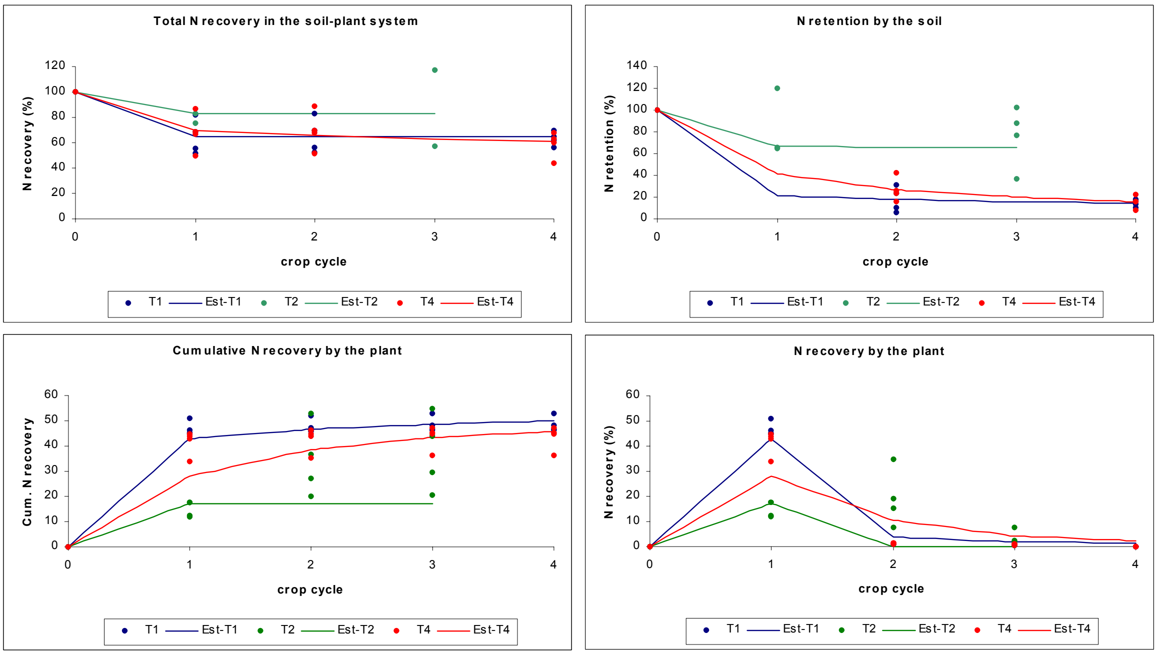

FIG. 14. Viet Nam: Fate of fertilizer N in a maize-soybean rotation. T1 = ^{15}N-labelled fertilizer and unlabelled crop residues added; T2 = unlabelled fertilizer and ^{15}N-labelled crop residues added; T4 = ^{15}N-labelled fertilizer added (no crop residues). Points represent values calculated for 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.

ACKNOWLEDGMENTS

We are grateful for financial support from the IAEA/FAO under Technical Contract 11134, and thank Dr. Gamini Keerthisinghe for encouragement and assistance.

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FERTILIZER NITROGEN RECOVERY UNDER DIFFERENT TILLAGE TREATMENTS AND CROPPING SEQUENCES IN A VERTISOL IN CENTRAL MEXICO

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Abstract

A field experiment was conducted to evaluate N use efficiency and the effect of residual N on yields of, and N uptake by, succeeding crops, as affected by crop rotation and tillage practices. There were six treatments: wheat-maize with conventional tillage and burning of residues (W-M/B), wheat-bean with conventional tillage and incorporation of residues (W-B/C), wheat-maize with conventional tillage and incorporation of residues (W-M/C), maize-bean rotation (M-B/B), wheat-maize without tillage and residues as surface mulch (W-M/NT), and wheat-bean without tillage and residues as surface mulch (W-B/NT). A study to determine the recovery and balance of ^{15}N-labelled fertilizer applied to winter wheat and to determine the uptake of residual N by succeeding crops (maize and bean) was conducted in 1996/97. The winter wheat received 300 kg N ha^{-1} as ammonium nitrate enriched with 5.011 at. % ^{15}N excess. Recovery of ^{15}N-labelled fertilizer in the crop at harvest in all treatments was small; less than 25% in the first season and less than 2% in the succeeding crops. Much of the fertilizer could not be accounted for in the crop or soil at harvest in both seasons, and is presumed lost. Losses averaged 70%. At wheat harvest, an important part of ^{15}N-labeled fertilizer remained in the soil profile, but apparently was not available for uptake in subsequent seasons. Prior fertilizer application had little effect on N uptake by subsequent crops. Slow movement of N down the soil profile during the season of application suggests that the fertilizer N was rapidly lost. In 1999/2000, different N-fertilizer sources were evaluated (urea, ammonium nitrate, and ammonium sulphate). In both seasons it was found that yields were in the order: ammonium sulphate > urea > ammonium nitrate. A study to determine the recovery and balance of ^{15}N-labelled fertilizer, applied to maize and bean, was conducted in 2000. The crops received 240 and 60 kg N ha^{-1}, respectively, as ammonium sulphate enriched with 5.468 at. % ^{15}N excess. The Ndff values ranged between 28 to 41% of the total N uptake for W-M/NT and W-M/C, respectively. The amount of fertilizer N remaining in the soil profile at harvest was 3.4 to 9.6%. With W-M/C, 9.6% of the ^{15}N-fertilizer remained in the soil at harvest, mostly in the 0- to 30-cm layer, probably due to immobilization. Unaccounted-for fertilizer N ranged between 27 to 69%. Considering that the soils had a predominantly clay texture and long periods of flooding occurred after irrigation, it is likely that considerable amounts of applied N were lost by denitrification.

1. INTRODUCTION

Cereals are grown on approximately 2×10^5 ha of Vertisols in the “El Bajío” region of central Mexico. During the past 30 years, a cereal-cereal rotation has been practised with continuously increasing rates of N-fertilizer application: from 120 kg N ha^{-1} in 1960 to 330 kg N ha^{-1} in 1999, possibly as a consequence of drastic diminishment in the content of organic matter of the soils (Fig. 1). Furthermore, in order to avoid overlap between the fall-winter and spring-summer cycles, crop residues are burned. The majority of the soils are low with respect to organic carbon (C) and nitrogen (N) due to intensive cropping, therefore N is the most-limiting nutrient. Despite past gains in wheat production though increased use of N fertilizers and irrigation, there are indications that the high fertilizer-N rates applied to crops are not efficiently utilized and are prone to losses by several mechanisms with potentially serious environmental consequences.

Therefore it is very important to study the dynamics of nitrogenous fertilizers in the region, especially in view of the fact that local agronomic and hydrologic characteristics favour the processes affect efficiency of use of N. Under these circumstances, conservation tillage offers a means of ameliorating this problem, but, to date, there has been little research on the effects of crop rotation and residue management on N use by wheat and N retention in the soil.

The objectives of this investigation were to evaluate N use efficiency and the effects of residual N on the yield and N uptake by succeeding crops, as affected by crop rotation and tillage practices in a Vertisol of Central Mexico.

2. MATERIALS AND METHODS

The field site was located at Instituto Nacional de Investigaciones Forestales, Agricolas y Pecuarias (INIFAP), Guanajuato, Mexico (20°44' N, 101°19' W, 1,750 m above sea level). The soil is classified as a Typic Pellusterts. It has a pH of 6.1 (1:2 water), an organic matter content of 2.2% and a clay texture. The region has an average of 650 mm of rain, mainly between June and August, with a mean annual temperature of 18°C (maximum average of 28°C and minimum average of 10°C).

2.1. Year 1

A detailed description of the treatments is given in Table I. The experiment was established in 1993. The data we report here correspond to the wheat crop that was planted in December 1996 and harvested at the beginning of May 1997. Maize and beans were planted in April 1997 and harvested in September 1997. The experiment design was a split plot with a randomized-block arrangement and four replicates.

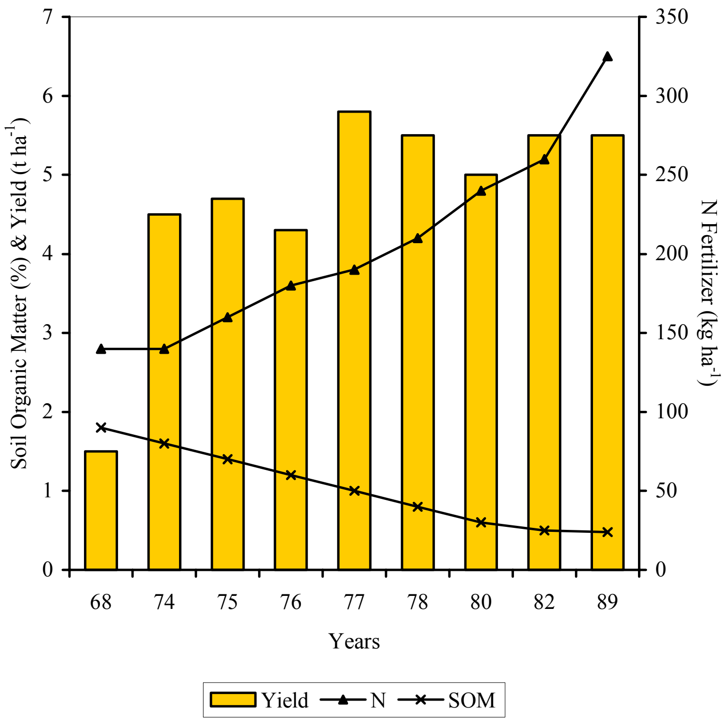

FIG 1. Wheat grain production, use of N fertilizers, and percentage of organic matter in soils of "El Bajío," Mexico [1].

Table I. Description of treatments

Treatment	Code	Crop rotation		Tillage	Residue management
		Winter	Summer		
1	W-M/B	Wheat	Maize	Conventional	Burning
2	W-B/C	Wheat	Bean	Conventional	Incorporation
3	W-M/C	Wheat	Maize	Conventional	Incorporation
4	M-B/B		Maize/Bean	Conventional	Incorporation
5	W-M/NT	Wheat	Maize	No tillage	Surface
6	W-B/NT	Wheat	Bean	No tillage	Surface

Tillage systems were the main plots and the fertilizer-N rates were the subplots. Before planting wheat, three rates of N fertilizer were applied in the five treatments: 0, 150 and 300 kg N ha^{-1} in the 10×10-m plots. In the treatments with 150 and 300 kg N ha^{-1}, 1×1-m microplots were delineated within every plot, to which were applied the same rate of N but with ^{15}N-labelled fertilizer as ammonium nitrate with 5.011 atom % excess.

After harvesting the wheat, maize and bean were established as succeeding crops. Nitrogen was applied at 240 and 60 kg ha^{-1} to maize and bean, respectively. Moreover, 10 t of wheat straw was either burned or spread on the soil surface or incorporated into the soil by rotavator from the ^{15}N microplots (2×2 m) of the main plots.

For the fertilizer-N balance study, plant samples were collected at harvest from the corresponding ^{15}N-labelled plot. Roots were disregarded. Soil samples were taken with a 4-cm diameter auger at five depths: 0 to 15, 15 to 30, 30 to 60, 60 to 90, and 90 to 120 cm. The soil samples were air-dried, ground to pass a 2-mm sieve and thoroughly mixed before subsampling. Total N contents was determined by the modified permanganate-reduced iron Kjeldahl method to include NO_3 and NO_2 [2]. Nitrogen-isotope ratios were determined on a mass spectrometer. Grain and straw yields were evaluated at the end of the seasons. Total and isotopic N analyses on the soil and plant material were made on samples collected at harvest. The calculations for estimating recovery in the plant and soil from ^{15}N-labelled fertilizer were made according to procedures described by Zapata [3]. The data were statistically analysed following standard ANOVA procedures and the significance of differences between mean values was determined at $P < 0.05$ by the LSD test [4].

2.2. Year 2

Annual crops in “El Bajío” are usually supplied with urea as the N fertilizer. Urea, ammonium sulphate and ammonium nitrate were evaluated for their agronomic effectiveness over two growing seasons. The split-plot design used a randomized-block arrangement and four replicates. Tillage system occupied the main plots and fertilizer-N sources were the subplots. Each subplot measured 4×30 m.

Urea, ammonium sulphate and ammonium nitrate were equally split at sowing and 40 days later. All fertilizer treatments received 320, 240, and 60 kg N ha^{-1} to winter wheat, spring maize and spring beans, respectively.

Determinations of dry matter production and N accumulation were made at harvest. The shoot material was harvested from 16 m^2. Fresh weights were recorded, chopped into 1- to 2-cm pieces, and subsampled. Subsamples were oven-dried at 70°C and weighed. Plant material was ground to pass a 0.5-mm sieve and analysed for total N content by the Kjeldahl method [5].

Table II. Wheat grain and straw yields, N assimilated, and %N derived from fertilizer

Treatment	Dry matter (kg ha^{-1})		N yield (kg ha^{-1})			Ndff (%)
	Grain	Straw	Grain	Straw	Total	
W-M/B	3,742	6,021	62.9	32.1	95.0	29
W-B/C	4,901	7,891	88.0	47.0	135	27
W-M/C	3,201	5,213	51.8	24.2	76.6	21
W-M/NT	4,027	6,026	63.0	26.2	89.3	21
W-B/NT	5,040	8,108	82.7	40.3	123	25
LSD	777	1,060	12.8	5.9	17.4	7.0
0 N	1,962	3,053	33.3	13.2	46.6	0.0
150 N	4,488	6,975	68.9	29.4	98.3	20
300 N	6,151	9,928	107	59.5	166	24
LSD	369	767	6.4	5.6	10.8	6.9

Table III. Nitrogen derived from fertilizer in soil layers

Treatment	Soil layers (cm) (kg N ha^{-1})					Total 0–120	Ndff (%)
	0–15	15–30	30–60	60–90	90–120		
W-M/B	39.2	13.9	11.3	4.5	2.0	70.9	36
W-B/C	32.6	13.4	12.2	3.4	2.8	64.6	29
W-M/C	41.1	13.0	10.2	4.5	2.3	71.1	32
W-M/NT	12.3	4.9	8.1	4.0	2.4	31.8	14
W-B/NT	22.1	7.5	6.9	3.8	1.8	42.3	19
LSD	13.6	4.9	6.7	2.2	0.8	22.1	9.8
150 N	19.4	7.2	6.0	2.8	1.5	36.9	25
300 N	39.6	13.9	13.4	5.3	2.9	75.2	25
LSD	9.1	2.9	3.6	1.0	0.7	14.3	NS

2.3. Year 3 (growing season 2000)

Maize and beans were grown after winter wheat in 2000. The experiment had a randomized complete block design with six treatments and four replicates; each ^{15}N microplot measured 1.5×1.5 m. Ammonium sulphate labelled with 5.468 at. % ^{15}N excess was applied as a solution to each ^{15}N microplot. It was equally split between at and 40 days later. Fertilizer treatments received 240 and 60 kg N ha^{-1} to maize and beans, respectively. Plant samples were taken from 1×1-m areas by cutting at ground level from each ^{15}N microplot. Fresh weights were recorded, chopped into 1- to 2-cm pieces, and subsampled. Subsamples were oven-dried at 70°C and weighed. Plant material was ground to pass a 0.5-mm sieve and analysed for total N content by the Kjeldahl method [5]. Nitrogen-15 enrichment values were determined using an NOI-6e emission spectrometer as described in [6].

For the fertilizer-N balance study, plant samples were collected at harvest from the corresponding ^{15}N-labelled plot. Roots were again disregarded. Soil samples were taken with a 4-cm diameter auger at the same five depths as before, then air-dried, ground to pass a 2-mm sieve and thoroughly mixed before subsampling. Total N contents were determined by the modified permanganate-reduced iron Kjeldahl method to include NO_3 and NO_2 [2]. Nitrogen-isotope ratios were determined as previously described.

The calculations for estimating recovery in the plant and soil from ^{15}N-labelled fertilizer were made according to the procedures described by Zapata [3]. The data were statistically analysed following standard ANOVA procedures and significance of differences between mean values was determined at $P < 0.05$ by the LSD test [4].

3. RESULTS AND DISCUSSION

3.1. Year 1

3.1.1. Winter season

Grain yields of wheat were higher when grown after beans either under conventional or no-till (Table II). The lowest yield occurred when wheat was planted after maize and crop residues were incorporated. The performance of the wheat was slightly improved when maize residues were left on the surface or burned. Yields and crop-N uptake increased with increasing N rate, and differences in yield between tillage treatments were minimized by N application. Nitrogen recoveries by the crop were higher when residues were burned or when beans were grown previously. Treatments with a large amount of residues resulted in lower N recoveries by the crop, especially if there were not ploughed in.

Less N was left in the soil in the no-till treatments, especially after maize (Table III). By adding the %N in plant derived from the fertilizer (Ndff) plus that left in the soil 0- to 120-cm layer after the wheat was harvested and subtract from 100, we calculate N losses; they ranged from 54 to 65% in the no-till treatments and from 35 to 48% in the conventional tillage treatments. These values are quite high as compared with those reported by Porter et al. [7], i.e. 10 to 13%. The source of N, the limited oxygen supply that normally occurs in Vertisols, the large amount of crop residues and compaction under no-till contributed to these high N losses.

Table IV. Tillage effects on dry-matter yields of succeeding crops of maize and beans (^{15}N microplots)

Treatment	Grain	Straw	Total
	(kg ha^{-1})		
W-M/B	7,765	12,515	20,280
W-B/C	1,469	1,898	3,367
W-M/C	7,397	11,415	18,811
W-M/NT	6,197	9,457	15,654
W-B/NT	901	1,295	2,196
LSD	482	783	1,173
0 N	2,827	4,499	7,324
150 N	4,976	7,830	12,811
300 N	6,436	9,614	16,050
LSD	369	756	1,054

Table V. Tillage effects on dry-matter yields of succeeding crops of maize and beans (straw-labelled microplots)

Treatment	Grain	Straw	Total
	(kg ha^{-1})		
W-M/B	9,583	15,007	24,589
W-B/C	1,487	1,987	3,474
W-M/C	9,044	13,623	22,667
W-M/NT	7,440	11,594	19,034
W-B/NT	975	1,411	2,386
LSD	597	1,401	1,853
150 N	4,976	7,835	12,811
300 N	6,436	9,614	16,050
LSD	371	692	1,021

Table VI. Tillage effects on the uptake of N by succeeding crops of maize and beans (^{15}N microplots)

Treatment	Grain		Straw		Total			Ndff
	N	^{15}N	N	^{15}N	N	^{15}N	Ndff	
	(kg N ha^{-1})							(%)
W-M/B	109	0.104	55.6	0.073	165	0.225	4.50	2.0
W-B/C	44.5	0.040	15.5	0.017	59.9	0.079	1.57	2.5
W-M/C	97.2	0.065	48.3	0.051	146	0.145	2.90	1.5
W-M/NT	81.7	0.054	39.9	0.030	122	0.106	2.12	1.4
W-B/NT	28.9	0.020	13.3	0.012	42.2	0.042	0.83	1.8
LSD	6.2	0.052	6.7	0.032	10.3	0.102	2.04	
0 N	36.3		18.8		55.1			
150 N	76.1	0.057	33.9	0.022	110	0.080	1.60	1.4
300 N	104	0.108	50.8	0.050	155	0.158	3.16	2.3
LSD	10.6	0.036	4.8	NS	28.6	0.158	3.16	

3.1.2. Summer season

Dry matter yields from ^{15}N and straw-labelled microplots (Tables IV and V) showed wide variation amongst the tillage and N-rate treatments. Conventional tillage plus burning residues and conventional tillage plus incorporation of residues resulted in higher dry matter production than did no-till. With 0-N, values ranged between 7,300 and 9,000 kg ha^{-1}, with 150-N, 7,000 to 12,800 kg ha^{-1}, and with 300-N, 15,000 to 17,000 kg ha^{-1}. Increases in crop dry weight with N-fertilizer application were statistically significant.

The values of total N and N derived form fertilizer (Ndff) in maize and bean are given in Tables VI and VII. The effects of N fertilizer and tillage system with regard to Ndff were significant. Again, a similar trend to that of dry matter was observed. With the 150-N treatment, the fertilizer N use was only 0.30 to 1.4%; at 300-N it ranged between 1.0 to 2.3%.

Table VII. Tillage effects on the N uptake of succeeding crops of maize and beans (straw-labelled microplots)

Treatment	Grain		Straw		Total			
	N	^{15}N	N	^{15}N	N	^{15}N	Ndff	Ndff
	(kg N ha^{-1})							(%)
W-M/B	148	0.074	75.7	0.031	224	0.105	2.107	0.92
W-B/C	47.5	0.140	16.5	0.006	64.2	0.020	0.392	0.61
W-M/C	133	0.056	63.6	0.012	197	0.078	1.564	0.71
W-M/NT	111	0.420	54.2	0.018	166	0.060	1.200	0.67
W-B/NT	32.0	0.008	13.7	0.004	45.8	0.013	0.253	0.60
LSD	11.9	0.030	7.7	0.012	18.4	0.042	0.850	NS
150 N	77.4	0.017	34.9	0.007	112	0.025	0.494	0.39
300 N	112	0.060	54.6	0.025	166	0.086	1.712	1.01
LSD	8.7	0.026	5.8	0.010	13.0	0.036	0.718	0.35

Table VIII. Percentage recovery in soil at harvest of succeeding crops, of ^{15}N-labelled fertilizer applied to wheat in the previous season

Treatment	Soil layer (cm)					Ndff (kg ha^{-1})
	0–15	15–30	30–60	60–90	90–120	
	(%Ndff)					
150 N						
W-M/B	0.64	0.29	0.099	0.19	0.20	2.13 ± 1.06
W-B/C	0.33	0.23	0.098	0.13	0.11	1.33 ± 0.719
W-M/C	0.55	0.32	0.00	0.096	0.073	1.55 ± 0.975
W-M/NT	0.56	0.24	0.11	0.13	0.077	1.68 ± 0.887
W-B/NT	0.38	0.34	0.23	0.15	0.14	1.86 ± 1.11
300 N						
W-M/B	1.2	0.94	0.22	0.12	0.13	7.96 ± 3.03
W-B/C	1.2	0.84	0.30	0.17	0.16	7.96 ± 2.02
W-M/C	1.3	0.76	0.15	0.14	0.08	7.27 ± 2.15
W-M/NT	0.42	0.29	0.18	0.098	0.078	3.20 ± 1.14
W-B/NT	0.75	0.44	0.15	0.078	0.069	4.45 ± 1.96

The values of Ndff in the soil were affected by the form of N source, being 1.3 to 7.9 kg N kg ha^{-1} in the ^{15}N microplots and 0.20 to 2.6 in the straw-labelled microplots (Tables VIII and IX). Again, Ndff in the soil increased as the rate of N increased. However, 90 to 96% of the Ndff in soil recovered at the beginning of the second cropping season could not be accounted for at final harvest.

Table IX. Percentage recovery in soil at harvest of succeeding crops, of ^{15}N-labelled wheat straw applied to soil

Treatment	Soil layer (cm)					Ndff (kg N ha^{-1})
	0–15	15–30	30–60	60–90	90–120	
	(%Ndff)					
150 N						
W-M/B	0.11	0.026	0.0008	0.095	0.00	0.353 ± 0.305
W-B/C	0.15	0.14	0.17	0.030	0.050	0.802 ± 0.656
W-M/C	0.049	0.026	0.0000	0.095	0.0021	0.251 ± 0.0979
W-M/NT	0.076	0.054	0.023	0.20	0.060	0.611 ± 0.303
W-B/NT	0.10	0.12	0.081	0.076	0.045	0.641 ± 0.463
300 N						
W-M/B	0.35	0.00	0.088	0.035	0.046	2.65 ± 2.13
W-B/C	0.46	0.16	0.13	0.059	0.057	2.60 ± 1.68
W-M/C	0.43	0.13	0.034	0.025	0.027	1.94 ± 1.02
W-M/NT	0.41	0.12	0.087	0.071	0.049	2.22 ± 1.41
W-B/NT	0.32	0.30	0.14	0.038	0.036	2.52 ± 1.07

Table X. Fertilizer-N balance after two growing seasons

Treatment	Recovery by the crops	Residual in the soil	Total accounted	Total non-accounted
	Ndff (kg N ha^{-1})			
W-M/B	91.2	4.5	95.7	204
W-B/C	82.0	1.6	83.6	216
W-M/C	65.0	2.9	67.9	232
W-M/NT	66.0	2.1	68.1	232
W-B/NT	76.7	0.80	77.5	223

In conclusion, different trends were observed in terms of dry matter yield under the tillage systems studied in two seasons. In both seasons higher levels of N significantly increased dry matter yield and N uptake compared to other N levels, although N efficiency of fertilizer was low. The recovery of ^{15}N-labelled fertilizer in the crop was small: less than 25% in the first season and less than 2% in the subsequent crops. Residual fertilizer N in soil after wheat harvest could be detected down to 120 cm, but most of it was present in the upper 60 cm. Similar trends were observed over the two cycles of experimentation although magnitudes differed.

This experiment shows that much of the fertilizer could be not accounted for in the crop or soil at harvest in either season, and was presumed lost. These losses averaged more than 70%. At wheat harvest, an important part of ^{15}N-labelled fertilizer remained in the soil profile (Table X). As reported in other studies [8–11], more fertilizer N remained in the soil than was recovered in the crop, but apparently it is not available for use in subsequent seasons, as shown by the need to constantly increase the rate of N fertilization in order to maintain yields.

The absence of movement of N down the soil profile during the season of application suggests that fertilizer N was rapidly immobilized and lost. Considering that our soil had a predominantly clay texture and long periods of flooding occurred after irrigation, it is likely that a considerable amount of applied N was lost by denitrification. Previous studies in the same type of soil in the same region revealed such losses of 15 to 25% of applied N [12,13]. There is need to optimize fertilizer management according to type, in terms of application technique and tillage, in order to match the supply of N with the needs of the crop to improve fertilizer use efficiency and minimize leaching and transformation into gaseous forms. This is a subject of current investigation.

3.2. Year 2

3.2.1. Summer season

Total dry matter and grain yields were consistently higher in no-till treatments (Table XI). Similarly, there were significant differences in total dry matter accumulation and grain yield between N sources, with the largest obtained with ammonium sulphate.

Nitrogen accumulations differed with tillage treatments (Table XII). At final harvest, the no-till systems significantly decreased the accumulation of N in the crop.

The effects of N-source and the interaction between tillage treatments with regard to N-accumulation and dry matter yields were significant. Again, a there was a tendency of accumulation of more N with higher yield for ammonium sulphate treatments (Table XIII).

3.2.2. Winter season

The dry matter production and N uptake were measured at harvest (Tables XIV, XV). Wheat dry-matter production was significantly higher when planted after beans either under conventional or no-till (Table XIV). The lowest yields occurred when wheat was planted after maize and no-till.

The dry-matter production was significantly influenced by N source, with the highest production obtained with ammonium sulphate (Table XIV).

The amount of N recovered in the crop was also affected by the form of fertilizer used (Table XV): N uptake was higher with ammonium sulphate than with urea or ammonium nitrate. The effects of N-source and the interaction between tillage treatments with regard to N-accumulation and dry matter yields were significant.

3.3. Year 3

Tillage system affected grain yields (Table XVI) and dry-matter production (Table XVII); the W-M/B and W-M/C treatments resulted in the higher dry-matter production than did no-till. In beans, M-B/B resulted in a higher dry matter production than W-B/C or W-B/NT. Treatment W-B/NT was lost as a result of periods of flooding after irrigation.

Results for N content are presented in Table XVIII. The same significant differences were observed between treatments as those for dry matter. The no-till treatments significantly decreased the accumulation of N in the crops. Nitrogen uptake is directly related to yield.

The values for %Ndff were small, except in W-M/C (41%) (Table XIX). There were highly significant differences with respect to Ndff values among tillage treatments. The averages for Ndff taken up by maize were 142, 99, and 66 kg N ha^{-1} for W-M/C, W-M/B, and W-M/NT, respectively. In beans, a larger Ndff value was observed with M-B/B.

Table XI. Tillage effects on dry-matter yields of maize (M) and bean (B), 1999

Factor	Straw		Grain		Total		Harvest index	
	M	B	M	B	M	B	M	B
	(kg ha^{-1})							
Tillage (T)								
W-M/B	11,404		7,456		18,860		0.38	
W-B/C		925		3,375		4,300		0.78
W-M/C	10,759		7,008		17,767		0.39	
M-B/B	12,594		7,319		19,913		0.37	
W-M/NT	9,303		6,249		15,552		0.40	
W-B/NT		632		1,274		1,906		0.66
LSD	504	141	439	156	642	161	NS	NS
Fertilizer (F)								
U	12,644	750	8,442	2,253	21,086	3,003	0.40	0.74
AS	14,381	874	9,250	2,806	23,631	3,680	0.39	0.74
AN	9,912	748	6,610	2,153	16,522	2,901	0.39	0.72
Control	7,123	887	3,729	2,087	10,852	2,974	0.35	0.69
LSD	715	79	510	298	979	NS	NS	NS
T × F								
W-M/B × U	13,375		8,922		22,297		0.40	
W-B/C × U		436		3,152		3,588		0.77
W-M/C × U	12,565		8,582		21,147		0.40	
M-B/B × U	14,338		9,694		24,032		0.40	
W-M/NT × U	10,298		6,571		16,869		0.39	
W-B/NT × U		562		1,354		1,916		0.70
W-M/B × AS	14,530		10,000		24,530		0.40	
W-B/C × AS		990		3,890		4,880		0.80
W-M/C × AS	13,632		9,446		23,078		0.41	
M-B/B × AS	17,355		8,864		26,219		0.34	
W-M/NT × AS	12,005		8,694		20,699		0.42	
W-B/NT × AS		758		1,721		2,479		0.69
W-M/B × AN	9,850		7,103		16,953		0.40	
W-B/C × AN		914		3,206		4,120		0.78
W-M/C × AN	9,850		6,471		16,321		0.40	
M-B/B × AN	10,392		6,606		16,998		0.39	
W-M/NT × AN	9,556		6,262		15,818		0.40	
W-B/NT × AN		583		1,099		1,682		0.67
W-M/B × C	7,860		3,800		11,660		0.32	
W-B/C × C		860		3,252		4,112		0.79
W-M/C × C	6,988		3,534		10,522		0.33	
M-B/B × C	8,290		4,113		12,403		0.34	
W-M/NT × C	5,355		3,470		8,825		0.39	
W-B/NT × C		626		1,548		2,174		0.59
LSD	1,430	152	987	516	1,813	715	NS	NS

Table XII. Tillage effects on total N yields of maize (M) and bean (B), 1999

Factor	Straw		Grain		Total		N harvest index	
	M	B	M	B	M	B	M	B
	(kg N ha^{-1})							
Tillage (T)								
W-M/B	92		103		195		0.52	
W-B/C		9.8		106		116		0.91
W-M/C	78		106		184		0.56	
M-B/B	95		115		210		0.53	
W-M/NT	64		92		156		0.58	
W-B/NT		6.8		45		52		0.86
LSD	8	1.4	8	11	10	12	0.04	0.01
Fertilizer (F)								
U	92	8.1	124	74	217	82	0.57	0.90
AS	106	9.3	139	100	245	110	0.57	0.91
AN	82	8.2	108	69	190	77	0.57	0.88
Control	49	7.6	44	61	93	69	0.47	0.86
LSD	6	1.0	6	5	9	5	0.03	0.02
T × F								
W-M/B × U	106		124		229		0.54	
W-B/C × U		9.9		101		111		0.91
W-M/C × U	86		128		213		0.60	
M-B/B × U	108		162		269		0.60	
W-M/NT × U	68		87		155		0.56	
W-B/NT × U		6.2		46		53		0.88
W-M/B × AS	113		141		253		0.56	
W-B/C × AS		10.5		130		141		0.92
W-M/C × AS	97		134		231		0.58	
M-B/B × AS	129		141		270		0.52	
W-M/NT × AS	86		142		227		0.62	
W-B/NT × AS		8.1		69		78		0.90
W-M/B × AN	93		104		196		0.53	
W-B/C × AN		10.2		100		111		0.91
W-M/C × AN	80		120		200		0.60	
M-B/B × AN	86		109		196		0.56	
W-M/NT × AN	68		99		166		0.60	
W-B/NT × AN		6.2		38		44		0.86
W-M/B × C	56		45		101		0.45	
W-B/C × C		8.7		94		103		0.91
W-M/C × C	48		43		91		0.48	
M-B/B × C	59		47		106		0.44	
W-M/NT × C	35		40		75		0.53	
W-B/NT × C		6.5		28		34		0.81
LSD	12	NS	11	NS	18	NS	NS	0.03

Table XIII. Effects of N source on grain yields

Fertilizer	Maize	Bean	Wheat
	(kg ha^{-1})		
Urea	8,442	2,806	7,190
Ammonium sulphate	9,250	2,153	8,125
Ammonium nitrate	6,610	2,087	7,330

Table XIV. Tillage effects on dry-matter production in wheat at final harvest, 1999–2000

Factor	Straw	Grain	Total	Harvest index
	(kg ha^{-1})			
Tillage (T)				
W-M/B	11,589	7,644	19,233	0.41
W-B/C	11,524	7,776	19,300	0.40
W-M/C	10,683	7,757	18,440	0.43
M-B/B				
W-M/NT	10,406	7,298	17,704	0.42
W-B/NT	12,129	7,600	19,729	0.40
LSD	1,016	288	939	NS
Fertilizer (F)				
U	10,233	7,190	17,423	0.42
AS	11,080	7,530	18,610	0.42
AN	12,486	8,125	20,611	0.40
LSD	1,050	229	1,092	NS
T × F				
W-M/B × U	9,540	6,531	16,071	0.40
W-B/C × U	10,207	6,790	16,997	0.40
W-M/C × U	10,465	7,605	18,070	0.42
M-B/B × U				
W-M/NT × U	9,942	7,096	17,038	0.43
W-B/NT × U	11,009	7,927	18,936	0.44
W-M/B × AN	11,548	7,641	19,189	0.44
W-B/C × AN	11,805	7,765	19,570	0.40
W-M/C × AN	10,585	8,057	18,642	0.46
M-B/B × AN				
W-M/NT × AN	10,019	6,831	16,850	0.41
W-B/NT × AN	11,443	7,355	18,798	0.39
W-M/B × AS	13,680	8,760	22,440	0.39
W-B/C × AS	12,560	8,772	21,332	0.41
W-M/C × AS	10,999	7,608	18,607	0.41
M-B/B × AS				
W-M/NT × AS	11,256	7,969	19,225	0.42
W-B/NT × AS	13,935	7,518	21,453	0.40
LSD	NS	511	NS	NS

Table XV. Tillage effects on total N yield in wheat at final harvest, 2000

Factor	Straw	Grain	Total	N harvest index
	(kg N ha^{-1})			
Tillage (T)				
W-M/B	74	143	218	0.66
W-B/C	81	163	244	0.67
W-M/C	76	139	215	0.64
M-B/B				
W-M/NT	61	130	190	0.68
W-B/NT	66	129	195	0.66
LSD	7	11	10	0.02
Fertilizer (F)				
U	61	130	191	0.68
AN	68	135	203	0.66
AS	86	158	244	0.64
LSD	5	5	8	0.04
T × F				
W-M/B × U	54	141	194	0.72
W-B/C × U	63	134	197	0.68
W-M/C × U	84	114	198	0.58
M-B/B × U				
W-M/NT × U	54	133	188	0.71
W-B/NT × U	50	127	177	0.72
W-M/B × AN	72	136	208	0.66
W-B/C × AN	76	152	228	0.67
W-M/C × AN	66	149	214	0.69
M-B/B × AN				
W-M/NT × AN	61	111	172	0.64
W-B/NT × AN	67	124	191	0.65
W-M/B × AS	98	152	250	0.61
W-B/C × AS	104	203	307	0.66
W-M/C × AS	77	154	231	0.67
M-B/B × AS				
W-M/NT × AS	67	145	212	0.68
W-B/NT × AS	82	136	218	0.62
LSD	12	12	17	0.04

There were highly significant differences in the recoveries of N among tillage treatments, e.g. 41 and 28% for W-M/C and W-M/NT, respectively (Table XX). Surprisingly, the use efficiency of fertilizer N in W-M/C was high, 59%, whereas in W-M/NT it was 27%. The low recovery of the high N rate (300 kg N ha^{-1}) in W-M/NT resulted in the non-uptake of 234 kg N ha^{-1} by the maize, constituting a risk of environmental pollution. There were significant contributions of N from the soil. At harvest, %Ndfs was to 59 to 72% of the total N.

Table XVI. Tillage effects on the grain yields

Treatment	Maize	Bean	Wheat
	(kg ha^{-1})		
W-M/B	10,535		7,520
W-B/C		2,009	8,391
W-M/C	10,835		7,704
M-B/B		2,466	
W-M/NT	8,569		8,024
W-B/NT		625	8,043

Table XVII. Tillage effects on dry-matter production in maize (M) and bean (B) at final harvest, 2000

Treatment	Straw		Grain		Total		Harvest index	
	M	B	M	B	M	B	M	B
	(kg ha^{-1})							
W-M/B	20,714a[a]		14,618a		35,332a		0.42a	
W-B/C		1,815b		1,774b		3,588b		0.49a
W-M/C	18,638a		14,416a		33,054a		0.44a	
M-B/B		2,602a		2,644a		5,246a		0.50a
W-M/NT	13,394b		10,487b		23,881b		0.44a	
W-B/NT		0c		0c		0c		0c

[a]Means within a column followed by same letter are not significantly different (LSD test; P <0.05).

Table XVIII. Tillage effects on total N yields of maize (M) and bean (B), 2000

Treatment	Straw		Grain		Total		N harvest index	
	M	B	M	B	M	B	M	B
	(kg N ha^{-1})							
W-M/B	94.4a[a]		250a		344a		0.73a	
W-B/C		22.5b		57.0b		79.5b		0.72a
W-M/C	100a		249a		349a		0.71a	
M-B/B		29.6a		84.8a		114a		0.74a
W-M/NT	69.1b		165b		234b		0.71a	
W-B/NT		0c		0c		0c		0c

[a]Means within a column followed by same letter were not significantly different (LSD test; P <0.05).

Values for Ndff residual in the soil are in Table XXI. The distribution of mineral N in the soil profile (0–120 cm) varied considerably between the two systems of management of residues. Approximately 21 kg N ha^{-1} (9% Ndff) of the fertilizer N applied to W-M/C were found in the 30-cm topsoil, whereas only 1 to 8 kg N ha^{-1} (3.3% Ndff) remained in the other treatments. When residues were incorporated, a considerable amount of fertilizer N was immobilized in the upper soil layer, probably due to heterotrophic microorganisms and a high availability of C. The amounts of fertilizer N at 30 to 120-cm were similar for all treatments (approximately 3 kg N ha^{-1}).

Table XIX. Tillage effects on the fertilizer-N uptake by maize (M) and bean (B) 2000

Trtmnt	Straw		Grain		Total		Fertilizer N recovery		N use efficiency	
	M[a]	B[b]	M	B	M	B	M	B	M	B
	Ndff (kg N ha^{-1})						(%)			
W-M/B	33.0b[c]		66.0b		99.0b		28.8b		41.2b	
W-B/C		7.0b		16.7b		23.7b		29.8a		39.5b
W-M/C	43.8a		98.0a		141.8a		40.6a		59.1a	
M-B/B		12.2a		28.4a		40.6a		35.5a		67.6a
W-M/NT	21.8c		44.0c		65.8c		28.1b		27.4c	
W-B/NT		0.0c		0.0c		0.0c		0.0c		0.0c

[a]Fertilized with 240 kg N ha^{-1} as ammonium sulphate enriched with 5.47 at. % ^{15}N excess.
[b]Fertilized with 60 kg N ha^{-1} as ammonium sulphate enriched with 5.47 at. % ^{15}N excess.
[c]Means within a column followed by same letter were not significantly different (LSD test; $P < 0.05$).

Table XX. Tillage effects on N uptake

Treatment	Ndff		Ndfs		N total	
	(kg ha^{-1})	(%)	(kg ha^{-1})	(%)	(kg ha^{-1})	(%)
W-M/B	99	29	245	71	344	100
W-B/C	24	30	56	70	80	100
W-M/C	142	41	207	72	349	100
M-B/B	41	36	74	64	115	100
W-M/NT	66	28	169	59	235	100
W-B/NT	0	0	0	0	0	100

Table XXI. Nitrogen derived from fertilizer in the soil profile at final harvest

Soil layer (cm)		Tillage treatment					
		W-M/B	W-B/C	W-M/C	M-B/B	W-M/NT	W-B/NT
		Ndff (kg N ha^{-1})					
0–15		5.49	1.30	12.20	1.06	2.39	0.82
15–30		2.41	1.00	8.72	1.00	2.17	0.43
30–60		1.67	0.76	0.78	0.62	1.50	0.33
60–90		1.24	0.25	0.23	0.23	1.18	0.32
90–120		0.76	0.24	0.11	0.23	0.82	0.18
Total	M	11.6b[a]		22.1a		8.09c	
(Ndff kg N ha^{-1})	B		3.56a		3.13a		2.11b
Total	M	4.8b		9.2a		3.4c	
(%Ndff)	B		5.9a		5.2a		3.5b

[a]Means within a row followed by same letter were not significantly different (LSD test; $P <0.05$).

Table XXII. Fertilizer-N balance

Treatment	Recovered by the crop		Residual in the soil		Total accounted		Total non-accounted	
	(%)	(kg N ha^{-1})	%	(kg N ha^{-1})	%	(kg N ha^{-1})	%	(kg N ha^{-1})
W-M/B	29	99.0	4.8	11.6	46	111	54	129
W-B/C	30	23.7	5.9	3.6	46	27.3	55	32.7
W-M/C	41	142	9.2	22.0	68	164	32	76.2
M-B/B	36	40.6	5.2	3.10	73	43.7	27	16.3
W-M/NT	28	65.8	3.4	8.10	31	73.9	69	166
W-B/NT	0.0	0.0	3.5	2.11	3.5	2.10	97	57.9

Taking into account the amounts of fertilizer N recovered in the plant and remaining in the soil, a total balance was established (Table XXII). The fertilizer N recovered in the plant-soil system for the six treatments ranged between 31 and 73%. Between 27 to 69% of the applied N could not be accounted for and presumably was lost as gaseous forms by denitrification or volatilization. In intensive cereal-cereal systems of Mexico, typical fertilization practices lead to high fluxes of nitrous oxide (N_2O) and nitric oxide (NO) [12–14].

Considering that our soil had a predominantly clay texture, and long periods of flooding occurred after irrigation, it is likely that considerable amounts of applied N werelost by denitrification. This possibility is under study.

4. CONCLUSIONS

The results of four years of experimentation show that:

- Nitrogen use efficiency in Vertisols during the first years under conservation tillage was very low, probably as a result of large amounts of crop residues and soil compaction.
- A bean-wheat rotation is a more efficient sequence in terms of crop yield and N use efficiency in the winter season.
- The W-M/C rotation was the more efficient sequence in terms of crop yield and N use efficiency in the summer season.
- The higher N application resulted in significant increases in grain and dry matter yields, but additional fertilizer N was utilized less efficiently.
- The amounts of fertilizer N normally applied for cereal production may be greatly in excess of crop needs.
- Straw incorporation can reduce N losses, and, in the long term, may significantly increase the organic-N content in the soil, and not result in decreased yields because of mineral-N immobilization in surface layers of the soil.
- Nitrogen-fertilization strategies in the “El Bajío” region should take account of low recovery of fertilizer N by the crop in the season of application in no-till systems, with large losses of fertilizer N, probably caused by denitrification in wet soils rich in organic residues.
- Yields of the cereal-cereal crop rotation were affected by the form of fertilizer applied, and can be summarized as follows: AS > U > AN.
- Residual effects of fertilizer-N application were not evident in this soil.
- The net negative balance (loss) of N was much higher with AN than with AS.
- It is likely that unassimilated fertilizer N contaminates not only groundwater by leaching of nitrates, but also the atmosphere as oxides of N by denitrification.
- Irrigation practices seem to be directly related to processes that result in losses of N.

ACKNOWLEDGMENTS

We are grateful to the Joint FAO/IAEA Division of the International Energy Agency, Vienna, Austria, Fundación Guanajuato Produce, A.C., and CONACYT-SIHGO for financial support. We thank Mr. A. Vera for skilled technical assistance and for carrying out the ^{15}N analysis on the emission spectrometer.

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RECOVERY OF FERTILIZER AND CROP-RESIDUE ^{15}N AND EFFECTS ON N FERTILIZATION IN THREE CROPPING SYSTEMS UNDER MEDITERRANEAN CONDITIONS

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Abstract

Our objective was to study the effects of crop residues on nutrient cycling and availability for a following wheat crop. The research program was conducted at three sites with differing climatic conditions: south Morocco (a wheat-wheat cropping system), central Morocco (sunflower-wheat), and the Atlas Mountains region (faba bean-wheat). Forty to 85 kg N ha^{-1} (9.764 at % excess ^{15}N) were applied in three doses. The fertilizer-N recovery by the wheat in the first year was 37%, by sunflower 33%, and by faba bean 37%. At harvest, 22 to 43% of fertilizer N was residual in the 0- to 80-cm soil profile. Twenty-three to 42% of the applied N could not be accounted for. Recovery of the residual labelled fertilizer N by the subsequent wheat crop was 3.4 to 13% for the treatment with residue incorporation and 3.6 to 10% for the treatment without residue incorporation and for the treatment with residues only (T2) 9.6 to 15%. The third crop recovered 1.2 to 6.8% for the treatment with residue incorporation and 0.59 to 6.2% for the treatment without residue incorporation, and 2.9 to 6.2 in T2.

1. INTRODUCTION

Three experiments were conducted in Morocco (south, central, and mountain regions). In the south, the Saharan region, agriculture is under irrigation with the use of increasing quantities of fertilizer N. The soils are poor with low organic matter content. Water is used efficiently by wheat and other crops in such conditions [1,2]. Mineral-N fertilizer is applied to wheat by local farmers at 170 kg N ha^{-1} [3]. Weber et al. [4] found that 60 kg N ha^{-1} is needed for each ton of cereal produced in West Africa.

Organic inputs are recommended to improve soil fertility for "low-input" agriculture to achieve sustainability [5]. Several low-input techniques to regenerate soil fertility are based on the incorporation of organic matter. Extensive research has been conducted to study the nutrient-supplying capacity of various organic materials, and combinations of the organic input and fertilizer N have been proposed as an attractive management option to solve problems of N deficiency in degraded soils [6,7].

Nitrogen fertilizer can amount to 15% of the production cost of wheat [8]. In Morocco, leaching of N below the root zone is unlikely between cropping seasons, because of low rainfall [2]. Similarly, anaerobic conditions that promote denitrification are rather infrequent during that period. Hence the residual N after harvest should be conserved during the fallow period and be available to the subsequent crop. As a result, recovery of the fertilizer N is expected to be high, either in the same season, or, when drought has limited N uptake by plants, in a subsequent season.

Breakdown of crop residues requires adequate moisture for microbial activity, and the diffusion of the nutritional elements produced during the decomposition process [9]. In a dry soil, N mineralization is reduced [10] and nitrification may cease [11]. Optimal moisture content for the decomposition of plant residues and further transformations is in the range 60 to 100% of field capacity [12]. Cycles of desiccation and moistening stimulate the activity of micro-organisms, favouring mineralization of N [13,14]. Similarly, Badaruddin et al. [15] showed that straw incorporation in the soil was more beneficial under increased moisture.

In situations where mineral fertilizers are scarce or expensive, management of crop residues is a major factor guiding the development of practices for optimizing nutrient use efficiencies by crops. In this context, the term synchronization is often used to describe the degree of concurrence in time and space of nutrient release from decomposing residues with the crop demand for those nutrients [16].

Residues with N content higher than 1.5% are able to directly increase the availability of N in the soil, and, consequently, can improve the yield of the crops [17,18]. On the other hand, Powlson et al [19] found that incorporation of 3 t ha^{-1} of wheat straw reduced loss of ^{15}N applied in autumn from 60% to 47% by immobilizing some of the excess nitrate. The immobilized N and the N originally in the straw is slowly mineralized and gradually becomes available for uptake.

Recoveries of residual N in alley-cropping systems have been widely studied [20–24]. A common finding has been the low recovery in a following wheat crop of N from residue. Vanlauwe et al. [22] estimated that 19% of leucaena N was recovered by the aboveground biomass of the leucaena hedgerow in two successive prunings. Ngoran et al. [23] found that the total recovery by maize of residue N and fertilizer N averaged 11% and 24%, respectively. Total fertilizer-N recovery decreased with increasing N application at two locations [25]. An important factor to be considered is poor synchrony between N release from residues and N demand by crops [23,26–28].

Similarly, several field experiments have revealed that total N recovery in the first crop derived from organic residues is very variable, but less than 20% [23,26,28]. Numerous factors affect rate of decomposition of organic residues. Inherent N content, C/N ratio, lignin and polyphenol concentrations, as well as climate conditions, influence decomposition rate and release of available N [29,30].

It has also been shown that soil properties can affect release of residue N [31,32]. On the other hand, most of the residue N is immobilized into a stable fraction of soil organic matter which may contribute to sustaining soil fertility in the long term [21,33]. Maintenance of soil organic matter is important for the long-term productivity of agroecosystems. The benefits of balanced fertilization, using crop residues to maintain levels organic matter in agricultural soils are increasingly emphasized [34,35].

The objective of this study was to evaluate the residual effects of the locally recommended rate of fertilization of wheat and the effects of incorporation of wheat residues on the productivity of a wheat-wheat cropping system, a sunflower-wheat system, and a faba bean-wheat system using ^{15}N.

2. MATERIALS AND METHODS

The experiments in the three locations were conducted in similar manner.

2.1. Southern Morocco

The experiment was conducted at the Tafilalet experimental farm for four successive growing seasons (1996–2000). Annual rainfall averaged only 97.8 mm (1996–1997) and 123 mm (1997–1998). The mean annual temperature was 18°C with a minimum of 8°C (January) and maximum of 30°C (July). The soil has a clay-loam texture (USDA classification) with the following physical-chemical characteristics: clay, 29%; loam, 34%; sand, 37%; total C, 0.68%; total N, 0.065%; and pH in water, 8.1 for the 0- to 20-cm layer. The experimental design was a randomized complete block with four treatments and four replicates, each plot measured 5×5 m.

2.1.1. 1996–1997

All sixteen plots were ploughed, fertilized with 125 kg P_2O_5 ha^{-1} and 56 kg K_2O ha^{-1} and seeded with wheat (*Triticum durum* cv. Karim) on December 22, 1996. Seeding depth was 3 cm. The plants were thinned to a spacing of 20 cm (160 kg ha^{-1}). To prevent sub-optimal plant growth, irrigations were applied in the manner used by local farmers.

Labelled N was added in three applications to 9-m^2 subplots of treatments T1 and T4, (i): at the rate of 28.2 kg N ha^{-1} as $(NH_4)_2SO_4$ enriched with 9.764 % at. ^{15}N excess at seeding. The remaining plots of Treatments T2 and T3, received the same quantity of unlabelled ammonium sulphate, (ii): T1 and T4 received N at the rate of 28.2 kg Nha^{-1} as $(NH_4)_2SO_4$ enriched with 9.764% at ^{15}N excess plus 24.8 kg N ha^{-1} as unenriched ammonium sulphate at tillering. The remaining plots (treatments T2 and T3) received the same quantities not enriched with ^{15}N, (iii): T1 and T4 received N at the rate of 28.2 kg N ha^{-1} as $(NH_4)_2SO_4$ enriched with 9.764% at. ^{15}N excess plus 24.8 kg N ha^{-1} as unenriched ammonium sulphate at flowering. The remaining plots (treatments T2 and T3) received the same quantity but not enrichment with ^{15}N.

The sixteen plots were harvested on June 1, 1997. Samples of grain, straw and roots were collected for total N and ^{15}N determinations. Soil samples were taken, at 0 to 20, 20 to 40, 40 to 60, and 60 to 80cm for total N and ^{15}N determinations.

2.1.2. 1997–1998

Wheat (*Triticum durum* cv. Karim) was supplied with 42 kg N ha^{-1} at sowing and 42 kg N ha^{-1} at tillering as $(NH_4)_2SO_4$. There were three treatments in four replicates, (i) T4: plant residues on plots fertilized with ^{15}N were removed, (ii) T1: plant residues on plots fertilized with ^{15}N were removed and plant residues (4.8 t ha^{-1}) chopped into 2- to 4-cm pieces not enriched with ^{15}N were transferred to plots that had received ^{15}N in the 1996–1997 season. (iii) T2: plots with ^{14}N application in 1996–1997; plant residues on plots fertilized with ^{14}N were removed and replaced with residues (4.8 t ha^{-1}) labelled with ^{15}N (from T1).

The straw contained 1.921% ^{15}N excess. The plots were harvested on June 1, 1998. Sampling was performed as in the 1996–1997 season. Differences between years and treatments were analysed using ANOVA, followed by LSD at the 0.05 probability level and T-test.

In growing seasons: 1998–1999 and 1999–2000, T1, T2, and T4 were applied as in the 1997–1998 growing season; T3 was used to produce wheat residues not enriched with ^{15}N, needed for T1.

Physical and chemical characteristics of the soil in southern Morocco were as follows:

Physical characteristics	Clay	Fine loam	Coarse loam	Fine sand	Coarse sand
	16%	28%	20%	30%	5.5%

Chemical characteristics	pH (H_2O)	pH (KCl)	E.C. at 25°C	N	O.M.	Exch. K	Avail. P_2O_5
	8.4	7.84	0.25 µS	0.069%	0.97%	5 ppm	8.8 ppm

Climate conditions at the experimental site in southern Morocco were as follows:

Season/ Month	Minimum temperature	Maximum temperature	Mean	Rainfall (mm)
	(°C)			
1996–1997				
September	13	31	22	0.5
October	7.7	26	17	2.3
November	1.8	21	11	0
December	0.16	16	8.3	32
January	1.4	15	8.3	29
February	1.7	19	10	0
March	4.5	22	13	4.8
April	9.5	23	16	18
May	13	29	21	1
June	16	35	25	0
July	20	38	29	1.3
August	19	34	26	9.1
1997–1998				
September	16	32	24	21
October	11	27	19	9
November	3.7	22	13	0
December	–1.1	18	8.5	0
January	–1.2	17	7.7	11
February	3.8	16.58	10	48
March	4.4	22	13	2.9
April	9.3	27	18	1.1
May	13	27	20	2.5
June	16	35	25	24
July	21	39	30	0
August	21	37	29	3.5
1998–1999				
September	15	32	23	0
October	9.6	2	18	0
November	3.0	22	13	2.5
December	–3.2	14	5.6	1.8
January	–1.9	15	6.7	15.3
February	–1.5	17	7.6	5
March	4.6	21	13	5.1
April	9.0	28	18	0
May	14	32	23	3.2
June	20	36	28	0.8
July	20	40	30	0
August	21	38	30	0

2.2. Central Morocco

The effects of sunflower residues on wheat were investigated in a 750-m^2 area that was ploughed, fertilized by 60 kg/ha of P_2O_5, 100 kg/ha of K_2O. Sixteen 16-m^2 plots were delineated. All plots were sown with sunflower variety VIKI on February 27, 1997. Seeding depth was 3 to 5 cm. Each plot contained six rows and the plants were thinned to a 20-cm spacing. Nitrogen was added in one application at 35 kg N/ha (250 g/plot of ammonium sulphate enriched with 10% at. ^{15}N excess) to eight plots, and the remainder received the same quantity of unenriched ammonium sulphate. The experiment was harvested on July 7, 1997, and the sunflower seeds were collected. Samples of soil and plant residue (leaves, stems, capitules and roots) were taken for dry weight, total N and ^{15}N determinations. The residues were then chopped into pieces of 2 to 7 cm. The residues were incorporated in rows at 40-cm depth on July 10, 1997 for the second phase of the experiment in 1997–1998.

The second crop, wheat, was planted on September 27, 1997, and harvested on December 1997. The third crop, sunflower, was planted on February 17, and harvested on June 30, 1998, then wheat was sown on September 25, and harvested on December 29, 1998. Then sunflower was sown on March 10 and harvested on July 1, 1999.

Physical and chemical characteristics of the soil at the experiment site in central Morocco were as follows:

Physical characteristics	Clay	Fine loam	Coarse loam	Fine sand	Coarse sand
	32%	30%	22%	6.5%	9.3%

Chemical characteristics	pH (H_2O)	pH (KCl)	E.C. at 25°C	N	$CaCO_3$	O.M.	Exch. K	Avail P_2O_5
	8.44	7.56	100 µS	0.12%	26%	3.0%	542 ppm	9.8 ppm

Climate conditions at the experimental site in central Morocco were as follows:

Season/Month	Minimum temperature (°C)	Maximum temperature (°C)	Mean (°C)	Rainfall (mm)
1996–1997				
September	18	31	24	15
October	16	26	21	40
November	9.0	19	14	0
December	5.6	12	8.6	200
January	6.7	15	11	200
February	5.0	20	12	75
March	6.0	24	15	100
April	7.0	23	15	30
May	10	24	17	80
June	15	27	21	12
July	17	31	24	5
August	18	32	25	0
1997–1998				
September	16	29	23	83
October	11	25	18	9
November	6.9	20	14	108
December	4.9	16	10	78
January	5.2	14	9.5	84
February	6.1	10	13	0
March	10	21	16	14

Season/Month	Minimum temperature (°C)	Maximum temperature (°C)	Mean (°C)	Rainfall (mm)
1997–1998	(continued)			
April	7.5	19	13	110
May	11	21	16	50
June	19	31	25	12
July	21	33	27	0
August	22	35	28	0
1998–1999				
September	16	28	22	22
October	11	26	19	6
November	6.9	20	14	0
December	4.9	16	10	35
January	3.5	16	9.5	63
February	6.0	14	9.9	62
March	6.0	21	13	23
April	7.0	19	13	21
May	16	21	18	92
June	18	31	25	16
July	19	33	26	0
August	20	34	27	0

2.3. Mountain region

The effects of bean residues on wheat were investigated at an Atlas mountain site. Nitrogen-15 was added at a total rate of 40 kg N/ha in two applications. A 500-m^2 area was ploughed, fertilized by 60 kg/ha of P_2O_5 and 100 kg/ha of K_2O. Twenty 16-m^2 plots were delimited. All plots were sown with faba bean on February 10, 1997, at a depth of 5 cm. The plants were thinned to a 20-cm spacing. Nitrogen was applied as ammonium sulphate on two occasion: 20 kg N/ha in February and the same on March 12, 1997, with 9.764 at. % excess ^{15}N.

The plots were harvested on the June 15, 1997. Seeds were harvested and the remainder of the plants was considered as residues (4,500 kg/ha). The ^{15}N-labelled residues were mixed and homogenized before being incorporated into the soil. The second crop, wheat, was sown on December 27, 1997, and harvested on June 15, 1998, then the third crop, faba bean, was seeded on February 25, 1999, and harvested on June 24, 1999.

Physical and chemical characteristics of the soil at the mountain-region site were as follows:

Physical characteristics	Clay	Fine loam	Coarse loam	Fine sand	Coarse sand
	0%	5%	3.5%	63.5%	28%

Chem. char's	pH (H_2O)	pH (KCl)	E.C at 25°C	N	O.M.	Exch. Mg	Diss'd Ca	Exch. K	Avail P_2O_5
	7.8	7.4	0.4 µS	0.09%	1.9%	1.0 mEq/100 g	15 mEq/100 g	92 ppm	56 ppm

Climate conditions at the mountain-region site were as follows:

Season/Month	Minimum temperature	Maximum temperature	Mean	Rainfall (mm)
	(°C)			
1996–1997				
September	18	31	24	80
October	16	26	21	42
November	9.0	19	14	105
December	5.6	12	86	201
January	6.7	15	11	141
February	8.0	20	14	6.0
March	12	24	18	13
April	9.7	23	16	116
May	12.8	24	18	33
June	13	27	20	19
July	18	31	25	2.0
August	19	32	26	2.0
1997–1998				
September	16	29	23	18
October	11	25	18	9.0
November	6.9	20	14	0
December	4.9	16	10	71
January	4.1	14	8.9	55
February	8.9	20	14	60
March	10	21	16	33
April	7.5	19	13	23
May	11	21	16	81
June	19	31	25	23
July	21	33	27	0
August	22	35	28	0
1998–1999				
September	16	28	22	20
October	11	26	19	10
November	6.9	20	14	18
December	4.9	16	10	65
January	4.1	16	9.8	82
February	2.7	14	8.2	35
March	4.6	21	13	42
April	9	19	14	25
May	16	21	18	32
June	18	3	25	24
July	19	33	26	0
August	20	34	27	0

3. RESULTS AND DISCUSSION

In Morocco, soils are poor and need inputs to produce a crop. Soil organic matter is the most important factor affecting productivity. In this work, in different regions and climates, we attempted to obtain better understanding of how fertilizer N is recovered by crops over five years. Our main methodological problem was to estimate ^{15}N enrichment in the soil, to calculate fertilizer-N level in the soil and thus estimate non-accounted-for fertilizer N for the second and third crops.

Table I. Dry matter yields and N-recovery data for the wheat-wheat cropping system (year 1, crop 1)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	4,781	3,585	155	3.03	37	4,709	1.8	22	42
SD	1,558	1,171	24.0	0.70	8.5	1,096	0.74	8.9	6.7
T2	3,868	2,902	134						
SD	920	690	17.3						
T3	4,152	3,114	137						
SD	1,577	1,183	45.3						
T4	4,597	3,423	170	2.65	32	4,724	1.7	20	48
SD	706	484	14.6	0.52	6.3	413	0.23	2.8	4.0

Table II. Dry matter yields and N-recovery data for the wheat-wheat cropping system (year 2, crop 2)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	8,525	6,448	271	0.70	8.5	4,921	3.14	38	17
SD	2,596	1,917	89.8	0.30	3.7	675	0.580	6.9	11
T2	8,057	6,046	216	0.16	2.0	4,845	0.950	12	0.05
SD	1,103	828	22.0	0.03	0.31	761	0.150	1.7	0.69
T3	9,547	7,150	299						
SD	1,141	847	36.9						
T4	7,235	5,428	228	0.57	6.9	4,901	3.24	39	22
SD	2,063	1,549	47.4	0.14	1.7	714	1.03	13	14

Table III. Dry matter yields and N-recovery data for the wheat-wheat cropping system (year 3, crop 3)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	4,515	3,136	129	0.15	1.8	4,190	1.98	24	29.
SD	1,666	916	57	0.06	0.76	363	0.27	3.3	6.4
T2	4,150	2,951	115	0.04	0.45	3,936	0.57	6.9	4.2
SD	1,299	821	30	0.01	0.12	566	0.20	2.4	2.0
T3	4,548	3,325	125						
SD	1,101	903	37						
T4	3,894	2,791	120	0.13	1.5	4,047	1.62	20	40
SD	1,518	1,057	38	0.03	0.32	673	0.34	4.2	3.6

Table IV. Dry matter yields and N-recovery data of the sunflower-wheat cropping system (year 1, crop 1)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	7,476	1,945	142	1.07	33	9,742	1.39	43	23
SD	604	146	17.9	0.08	2.4	208	0.14	4.3	5.3
T2	6,731	1,888	117						
SD	923	140	9.21						
T3	6,772	2,200	133						
SD	810	356	16.9						
T4	7,359	2,018	127	0.88	28	9,748	1.85	58	15
SD	978	96.9	24.6	0.28	8.9	369	0.24	7.4	4.3

Table V. Dry matter yields and N-recovery data for the sunflower-wheat cropping system (year 2, crop 2)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	8,481	2,539	160	0.07	2.2	7,335	1.57	49	15
SD	812	250	26.2	0.02	0.76	762	0.22	7.0	7.2
T2	8,251	3,269	166	0.08	2.5	7,429	0.4	13	2.6
SD	979	405	22.8	0.03	0.86	360	0.08	2.7	1.8
T3	8,505	3,009	164						
SD	927	211	7.1						
T4	8,728	2,839	166	0.08	2.6	6,863	1.58	49	20
SD	516	269	11.2	0.01	0.19	528	0.03	1.0	8.9

3.1. Southern Morocco

In the wheat-wheat cropping system where 8.4 kg ^{15}N/ha was added to soil, Table I shows that wheat recovered 3.03 kg ^{15}N/ha, the soil contained 1.79 kg and the non-accounted value was 3.5 kg. So wheat recovered 37% of the added fertilizer. The second wheat crop, in treatment T1 (with residues) recovered 13% of the fertilizer N (Table II). The soil contained 38% of the applied fertilizer N. In T4 (without residues) only 7% of added ^{15}N was recovered by wheat, indicating that crop residues increased N uptake; the soil recovered 39% of added ^{15}N. In T2, the crop recovered 15% of the N in the residues, and the soil in this case retained 85% of the N in the residues. In the third crop, wheat, recovery by plants in T1 was 1.8% of added fertilizer N and 24% remained in the soil (Table III). In T4, wheat recovered only 1.2% of added N and the soil recovered 40%. In T2, wheat recovered 3.9% of the residue N, and 59% remained in the soil.

3.2. Central Morocco

In the sunflower-wheat-cropping system, sunflower recovered 33% of the added fertilizer N. Soil retained 43% of added N, thus 23% of N was unaccounted for (Table IV). In the second crop, wheat recovered 2.2% of fertilizer N in treatment T1 (with residues) (Table V). The soil retained 49% of added N and 15% was lost. In T4, wheat recovered 2.6% of added N, showing no beneficial effect of sunflower residues on recovery of N by the following wheat crop. The soil recovered 49% of added N and the non-accounted for value was only 20%. In T2, wheat recovered 4.9% of the N in the sunflower residues, showing that sunflower residues increased N uptake by wheat and improved wheat N nutrition. The soil in this case retained 71% of the N added in the sunflower residues. In the third crop, in T1 sunflower recovered only 4.3% of added N and 47% was in the soil, with 13% unaccounted for (Table VI). In T4, the sunflower recovered a similar quantity of ^{15}N (4.1%) and 49% remained in the soil. The unaccounted-for N was 17%. In T2, sunflower recovered 6.2% of residue N and 78% of residue N remained in the soil.

3.3. Mountain region

In the faba bean-wheat cropping system, the bean crop took up 37% of the added fertilizer and the rest was either recovered in soil (36%) or lost (28%) (Table VII). In the second crop, the wheat in treatment T1 (with faba-bean residues) recovered 6.3% of added N, 34% remained in the soil, and 23% was unaccounted for (Table VIII). In T4 (without residues), only 5.3% of added N was recovered by the wheat showing a beneficial effect of bean residues on subsequent recovery of N; again, the soil retained 34% of added N. In T2, wheat recovered 9.5% N from the residues. In this case the soil recovered 80% of the N in the faba-bean residues.

Table VI. Dry matter yields and N recovery data for the sunflower-wheat cropping system (year 3, crop 3)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	9,394	1,228	108	0.14	4.3	8,830	1.15	47	13
SD	1,851	753	34.7	0.05	1.7	394	0.12	3.8	2.8
T2	9,046	939	82.5	0.03	0.90	8,846	0.37	11	2.7
SD	1,911	96	7.3	0.01	0.17	531	0.03	1.1	2.7
T3	9,228	3,325	147						
SD	879	903	37.6						
T4	8,785	1,905	118	0.13	4.1	8,842	1.56	49	17
SD	1,771	746	23.5	0.03	0.95	442	0.15	4.8	11

Table VII. Dry matter yields and N-recovery data for the faba bean-wheat cropping system (year 1, crop 1)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	4,063	2,790	224	1.56	37	5,407	1.52	36	28
SD	396	157	10.9	0.07	1.6	321	0.74	17	18
T2	3,882	2,649	214						
SD	922	395	35.2						
T3	3,868	2,849	222						
SD	658	206	2.7						
T4	3,928	2,939	235	1.64	39	5,244	1.63	38	23
SD	243	267	22.8	0.16	3.7	115	0.19	4.6	4.08

Table VIII. Dry matter yields and N-recovery data for the faba bean-wheat cropping system (year 2, crop 2)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	4,094	3,168	79.2	0.27	6.3	6,027	1.45	34	23
SD	774	362	16.0	0.20	4.6	530	0.21	4.9	8.6
T2	4,668	3,494	78.7	0.05	1.3	6,074	0.45	11	1.4
SD	338	258	15.1	0.01	0.26	430	0.05	1.1	1.5
T3	4,615	3,582	81.2						
SD	387	350	11.9						
T4	5,000	4,081	93.2	0.23	5.3	6,069	1.44	34	22
SD	416	595	19.6	0.09	2.09	526	0.19	4.4	7.1

Table IX. Dry matter yields and N-recovery data for the faba bean-wheat cropping system (year 3, crop 3)

Trtmnt	Yield		Plant			Soil			Not accounted for
	Residue	Grain	Total N	^{15}N	Recovery	Total N	^{15}N	Recovery	
	(kg/ha)		(kg/ha)		(%)	(kg/ha)		(%)	(%)
T1	4,247	2,636	220	0.03	0.68	7,417	1.54	36	20
SD	947	388	31.9	0.03	0.82	266	0.20	4.7	9.2
T2	3,804	2,582	208	0.01	0.35	7,243	0.38	8.8	2.9
SD	673	287	26.0	0.00	0.10	101	0.05	1.1	1.6
T3	4,208	2,858	231						
SD	802	673	43.2						
T4	3,894	2,356	204	0.01	0.33	7,072	1.30	30	25
SD	1,518	598	53.9	0.01	0.18	477	0.17	4.1	7.7

In the third faba-bean crop, plants in T1 recovered only 0.68% of added N, and the soil recovered 36%; 20% was unaccounted for (Table IX)—showing similar effects as in the other two locations. In T4, faba bean recovered similar quantities of ^{15}N (0.33% of added N), soil recovered 30% of added N, and 25% was unaccounted for. In T2, faba bean recovered 2.9% from residue N; the soil recovered 74%.

4. CONCLUSIONS

The three experiments conducted at different sites and with different cropping systems showed similar trends in terms of the fate of fertilizer N over several years of cropping. In general, only about 35% of the fertilizer N was recovered by the first crop, the rest was either retained by the soil or lost by volatilization or drainage. This highlights the need for improved fertilizer-management practices. Residue application to soil improved N nutrition of crops, but longer-term effects need to be investigated. Residual effects of fertilizer were similar to addition of crop residues. A modelling approach is needed to synthesize the data to obtain meaningful information to assist in the development of improved management practices for efficient use of fertilizer N and residues.

ACKNOWLEDGMENTS

We gratefully acknowledge the financial support of the International Atomic Energy Agency (IAEA). We thank Drs. Gamini Keerthisinghe and Felipe Zapata for their help and advice, and we thank the technical staff of the IAEA Seibersdorf Laboratory for ^{15}N analyses. The SEMVA of Tafilalet, the National School of Agriculture and the Centre of Qualification in Bouderbala, where the research was conducted, are gratefully acknowledged.

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QUANTIFYING BELOW-GROUND NITROGEN OF LEGUMES: OPTIMIZING PROCEDURES FOR ^{15}N SHOOT-LABELLING

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Abstract

Quantifying below-ground nitrogen (N) of legumes is fundamental to understanding their effects on soil mineral N fertility and on the N economies of following or companion crops in legume-based rotations. Methodologies based on ^{15}N-labelling of whole plants with subsequent measurement of ^{15}N in recovered plant parts and in the root-zone soil have proved promising. We report four glasshouse experiments with objectives to develop appropriate protocols for in situ ^{15}N labelling of four pulses, faba bean (*Vicia faba*), chickpea (*Cicer arietinum*), mung bean (*Vigna radiata*) and pigeon pea (*Cajanus cajan*). Treatments included ^{15}N-urea concentration, feeding technique, leaflet/petiole position, and frequency of feeding. Nitrogen-15-labelling via the leaf-flap was best for faba bean, mung and pigeon pea, whilst petiole feeding was best for chickpea, in all cases using 0.2-mL volumes of 0.5% urea (98 atom% ^{15}N excess). The implications of uneven enrichment of the nodulated roots because of effects of the ^{15}N-depleted nodules when calculating root-derived N in soil are discussed.

1. INTRODUCTION

Until recently, little was documented on the proportions of crop plants, particularly legumes, that are below ground or on the significance of this N source to the net mineralization of N in the soil. Accurate information on both is fundamental to quantifying legume effects on soil mineral N and on the N economies of cereal crops in legume-cereal rotations.

Because of the difficulties and errors associated with estimating below-ground N (BGN) of plants by physically recovering roots, considerable effort has been put into development of methods, in which plants are ^{15}N-labelled during early growth and the label (and distribution of N) quantified later in shoots, roots and root-zone soil [1–5]. Requirements of this approach are that the whole plant (i.e. shoots and roots) is enriched with ^{15}N and that root-zone soil should not be directly labelled with ^{15}N. In other words, any ^{15}N in the soil should be of plant origin.

Different labelling protocols have been reported, most often in the context of environmental research or to study the deposition of N-rich compounds and decaying root material in the plant's rhizophere, termed rhizodeposition. For example, Janzen and Bruinsma [6] grew wheat plants in the presence of $^{15}NH_3$ (multiple pulses) and determined the distribution of the ^{15}N between shoots, roots and soil. Other studies have used $^{15}N_2$ [7,8].

Shoot labelling is technically less demanding than atmospheric labelling. Nitrogen-15 has been applied in a foliar spray of urea [9], by immersing attached whole and detipped leaflets in vials containing enriched ammonium sulphate [4] and urea [5,10], by immersing attached petioles in vials containing urea [11], via a cotton-wick inserted into a hole in the stem and linked at the other end to a reservoir of labelled urea [1,2], and by injecting enriched urea into the plant's stem [11].

A third approach to ^{15}N labelling involves exposing part of the root system to a solution of ^{15}N and recovering the label in the shoot and the other non-exposed part of the root (i.e. split-root system) [3,4,12].

All three approaches, and the various labelling techniques within those approaches, have been developed for particular purposes, and each has distinct advantages and limitations. It is unlikely, therefore, that any one technique will be broadly applicable to all legume species. Some of the techniques require complex and/or expensive equipment (e.g. gas-tight enclosures), some have specific plant morphological requirements (e.g. woody or hollow stems), while others result in the substantial disturbance of the plant-soil system (split-root technique) or pose potential risks of soil contamination via run off from foliage of applied ^{15}N (spray application).

The most straight-forward and effective of the techniques appears to be ^{15}N labelling via leaflets or petioles. It has been used successfully in glasshouse and field studies involving large crop plants [pea (*Pisum sativum*), faba bean (*Vicia faba*) and barley (*Hordeum vulgare*)] and small pasture species [subterranean clover (*Trifolium subterraneum*) and serradella (*Ornithopus compressus*)] [4,5,10,11]. It remains to be seen whether leaflet/petiole feeding has application to other species, particularly other pulses.

In this paper we report the first set of experiments to quantify BGN of the pulses. The objectives of the glasshouse experiments were to evaluate and develop appropriate protocols for in situ ^{15}N labelling of four pulses, faba bean, chickpea (*Cicer arietinum*), mung bean (*Vigna radiata*) and pigeon pea (*Cajanus cajan*). Treatments included ^{15}N-urea concentration, feeding technique, leaflet/petiole position, and frequency of feeding.

2. MATERIALS AND METHODS

2.1. Plant material and culture

Eight seeds of each of the four pulses, faba bean cv. Fiord, chickpea cv. Amethyst and Moree (Expt. 4 only), mung bean cv. Berken and pigeon pea cv. Quantum, were sown into each pot containing either a N-free growth medium (sand-vermiculite) or a soil-based potting mix. For Experiments 1 to 3, plants were grown in 11-L free-draining plastic pots (24 cm diameter × 24 cm deep) filled with a 50:50 mixture of sand and vermiculite (Table I). The sand-vermiculite medium was used to facilitate the recovery of nodulated roots. In Experiment 4, 23-L free-draining pots (28.5 cm diameter × 40 cm deep) were used, each containing 22 kg of a 50:50 mixture of sand and soil.

Each pot was inoculated with 100 mL of a 5% suspension of commercial rhizobial inoculant. Strains used were: *Rhizobium leguminosarum* bv. Viciae SU 303 for faba bean; *Mesorhizobium ciceri* CC 1192 for chickpea; *Bradyrhizobium* spp. CB 1015 for mung bean and *Bradyrhizobium* spp. CB 1024 for pigeon pea. Pots were located for the duration of each experiment in a naturally lit, temperature-controlled glasshouse (27°C day/22°C night).

Plants were supplied daily with either N-free complete nutrient solution [13] or tap water. Ten days after germination, the seedlings were thinned to either four (N-free medium) or six (soil) plants/pot. Each ^{15}N experimental treatment consisted of three to five replicated pots. For the soil experiments, additional natural abundance control pots were included in which plants were not fed with ^{15}N-labelled urea.

Table I. Glasshouse experiments to optimize ^{15}N-labelling procedures

Objective	Species	Growth medium
Experiment 1		
To examine the effect of concentration of urea on shoot necrosis and on ^{15}N enrichment of roots	Faba bean chickpea mung bean pigeon pea	Sand-vermiculite
Experiment 2		
To compare petiole and leaf-flap ^{15}N feeding techniques in terms of root ^{15}N enrichment	Mung bean pigeon pea	Sand-vermiculite
Experiment 3		
To determine the effect of leaf position and multiple feeding on root ^{15}N enrichment	Faba bean chickpea	Sand-vermiculite
Experiment 4		
To compare the uniformity and distribution of ^{15}N in above-ground and below-ground parts	Faba bean chickpea	Soil-sand

2.2. Nitrogen-15 shoot-labelling techniques

Preliminary experiments were undertaken to evaluate a number of shoot-labelling techniques. Specific problems were encountered with some approaches. For example, the cotton-wick technique of Russell and Fillery [1] resulted in excessive damage to the lower stem, particularly with faba bean and chickpea, and occasional lodging. Stem injection [11] was also considered unsuitable because, of the four species, only faba bean has hollow stems. Even so, the volumes that could be accommodated by the glasshouse-cultured faba bean were very small (<0.1 mL) and often a positive pressure was generated with injection so that some ^{15}N-solution leaked back to the exterior of the stem, where it could have been washed onto and contaminated the soil surface. Two feeding techniques, leaf-flap and petiole, were consistently successful and were used in all subsequent studies.

2.2.1. Leaf-flap feeding of ^{15}N

The leaflets of faba bean, mung bean, and pigeon pea, but not of chickpea, are large enough for leaf-flap feeding, described by Pate et al. [14]. The selected attached leaflet was first placed in a Petri dish containing water so that it was fully submerged. A narrow "V," with the end of the "V" centred on the mid vein close to the leaf tip, was then cut out to form a flap. The flap was immediately inserted into a small plastic tube containing 0.2 mL of ^{15}N solution, and kept in place with Blu-Tack (Bostik Thomastown, Victoria, Australia). The Blu-Tack also served to seal the top of the tube to prevent evaporative losses and to attach the tube to a small wooden stake placed next to the leaf. Generally, all the ^{15}N-solution was taken up within 2 to 3 h. If the ^{15}N-solution remained in the vial overnight, the procedure was repeated using another leaflet.

2.2.2. Petiole feeding of ^{15}N

The petioles of chickpea, mung bean and pigeon pea, but not of faba bean, are sufficiently long for the ^{15}N-solution to be fed through them (once the leaflets were detached), although the procedure was slightly different for each species. With mung bean, only the middle leaflet of the trifoliolate was removed from its petiole. With pigeon pea, petiole connections to all the three leaflets had to be cut. For chickpea, leaflets near the tip of the petiole were cut under water, leaving some towards the bottom of the petiole. In all cases, the tip of the petiole was cut under water before being placed in a small tube containing 0.2 mL ^{15}N-solution, as described above.

Feeding of ^{15}N using either the leaf-flap or petiole technique was commenced 40 days after sowing, prior to flowering for all species, when the plants were at the eight- to ten-node stage. All experiments involved the use of ^{15}N-enriched urea (98 atom % excess, Isotech Inc., Matheson, USA) solutions of varying concentrations.

2.3. Experimentation

A summary of the four glasshouse experiments, conducted during the spring and summers of 1996 and 1997, is presented in Table I. Further details are provided in the following sections.

2.3.1. Experiments 1 and 2: Effects of urea concentration on shoot necrosis and on ^{15}N enrichment of roots, and a comparison of leaf-flap and petiole-feeding techniques

Urea has been widely used for ^{15}N labelling of plants because it is non-toxic at low concentrations and it is readily absorbed by plant tissues to be hydrolysed to ammonium carbonate by ureases. The labelled ammonium is rapidly synthesized into amino compounds, which are subsequently translocated to the rest of the plant. In this way, ^{15}N label is distributed to all parts of the shoot and root.

When using ^{15}N-urea shoot-feeding procedures, the challenge is to supply sufficient label in order to generate the desired level of ^{15}N enrichment of the plant while avoiding tissue necrosis, or, in worst-case scenarios, plant death. There is the concern that excessive tissue damage may interfere with the uptake of urea and/or subsequent translocation of the ^{15}N out of the fed organ. The result would be low and variable enrichments of ^{15}N in the target tissues.

Although previous investigations have reported relationships between urea concentration and tissue necrosis for various plant species [5,15], no information was available for the four pulses used in this study. Consequently, four concentrations of ^{15}N-urea solution (0.1%, 0.5%, 1%, and 2% w/w) were prepared and 0.2-mL volumes of each were fed either via a leaf-flap (faba bean, mung bean, pigeon pea) and/or a cut petiole (chickpea, mung bean, pigeon pea) at a leaf near the base (node 3 or 4) of each plant. The degree of necrosis was visually rated from nil (no damage) to 5 (death of entire leaflet or petiole) (Experiment 1). Since two alternative shoot-feeding procedures were applied to mung bean and pigeon pea, the levels of root ^{15}N enrichment achieved using both the leaf-flap and petiole-feeding technique could also be compared in the same experiment (Experiment 2).

2.3.2. Experiment 3: The effect of leaf position and multiple feeding on ^{15}N enrichment of roots

Published information suggests that there may be preferential partitioning of assimilates from legume leaves either belowground or to developing shoot meristems and fruit depending upon the leaf position in the plant architecture [e.g. 16]. To compare the effect of feeding location on subsequent ^{15}N enrichment of roots, faba bean and chickpea were fed 0.2 mL of 0.5% ^{15}N-urea to leaflets or petioles either at the lower three nodes of the plant, or at the fully expanded leaf immediately below the main-stem apical meristem. In order to determine the effect of feeding more than once on root ^{15}N enrichment, replicate pots of plants were fed with 0.2 mL of 0.5% ^{15}N-urea at the base on two occasions, 1 week apart.

2.3.3. Experiment 4: Comparison of the uniformity and distribution of ^{15}N in above-and below-ground plant parts

The objective in this experiment, involving two cultivars of chickpea and one of faba bean, was to determine the uniformity of ^{15}N-labelling by partitioning the plant and assessing ^{15}N-enrichment of the various fractions. Plants were fed with ^{15}N-urea three times prior to flowering, using the leaf-flap technique for faba bean and petiole feeding for chickpea, then grown until late pod-fill when the various components of the shoots and roots were separated for analysis.

2.4. Plant harvest

The fed leaflets and petioles were always removed within 2 weeks of feeding. The labelled plants (minus fed leaflets and petioles) were harvested 4 weeks after the final feeding in Experiments 1 to 3, and at late-pod fill (around the time of peak biomass) in Experiment 4. Fallen leaves were collected regularly during the course of the experiments to minimize ^{15}N contamination of the root-zone potting mix or soil.

At harvest, plants were decapitated and roots were carefully removed from the potting mix or soil. They were then separated into (a) taproots, which included the intact root crown, taproot, and major laterals, and (b) the distal roots, which represented other macro-roots and root fragments recovered from the potting mix.

In Experiment 4, nodules on three of the six taproots from each pot were removed from roots so that they and unnodulated roots could be analysed separately. Thus, recovered roots were separated into nodulated taproots, taproots with nodules removed, distal roots, and nodules. At the same time, shoots were divided into three equal portions (upper, middle and lower) and the stems, leaves and fruits separated in each stratum. All root and shoot samples were oven-dried at 70°C for at least 3 days and dry weights recorded.

2.5. Total N and ^{15}N analyses

The dried plant material was coarsely ground in a Wiley mill (1-mm sieve), subsampled, and then finely ground to a powder with a ring grinder (Rocklabs Pty Ltd, Auckland, New Zealand). The total N content and ^{15}N enrichment of the dried, ground samples were determined by combustion using an automatic N and C analyser interfaced with a 20-20 stable isotope mass spectrometer (Europa Scientific, Crewe, United Kingdom). The ^{15}N data were expressed as $\delta^{15}N$ or parts per thousand (‰) relative to the ^{15}N composition of atmospheric N_2 (i.e. 0.3663 atom% ^{15}N), as follows:

$$\delta\,^{15}\mathrm{N} = 1000 \times \frac{(\mathrm{atom\%}\ ^{15}\mathrm{N}_{\mathrm{sample}} - \mathrm{atom\%}\ ^{15}\mathrm{N}_{\mathrm{air}})}{(\mathrm{atom\%}\ ^{15}\mathrm{N}_{\mathrm{air}})}$$

3. RESULTS

3.1. Experiments 1 and 2: Effects of urea concentration on shoot necrosis and on ^{15}N enrichment of roots, and comparison of leaf-flap and petiole-feeding techniques

Faba bean, chickpea, mung bean and pigeon pea grew well, with no effects on dry matter (DM) of shoots or roots of any of the concentrations of ^{15}N-enriched urea solutions (0.1%, 0.5%, 1%, and 2%) or by the feeding technique. Shoot DMs were in the range 72 to 90 g/pot for faba bean, 51 to 62 g/pot for chickpea, 102 to 123 g/pot for mung bean, and 79 to 100 g/pot for pigeon pea. However, effects of increasing concentrations of urea on leaflet necrosis were large and consistent amongst the pulses. Damage was negligible for 0.5% urea, whereas necrosis of the entire leaf flap and petiole occurred with the 2% solution. Petioles were more tolerant of the higher urea concentrations than the leaflets (mung bean and pigeon pea comparison only). Potential for contamination of the rooting medium by detached highly enriched fed petioles was considered to be a risk with urea concentrations >0.5%.

Almost all the ^{15}N-urea was generally taken up within 2 to 3 h except for the higher urea concentrations where 10 to 30 μL (5–15%) of solution often remained. This suggested tissue damage caused by the urea since the volume of residual ^{15}N solution that remained generally reflected the degree of necrosis observed.

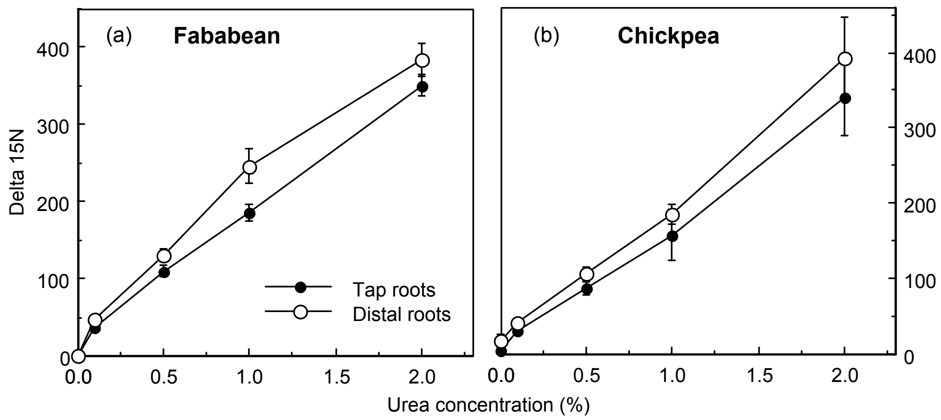

FIG. 1. The effects of urea concentration used for (a) leaf-flap feeding of faba bean and (b) petiole-feeding of chickpea on the ^{15}N enrichment of tap and distal roots. Error bars indicate ± standard error of the mean.

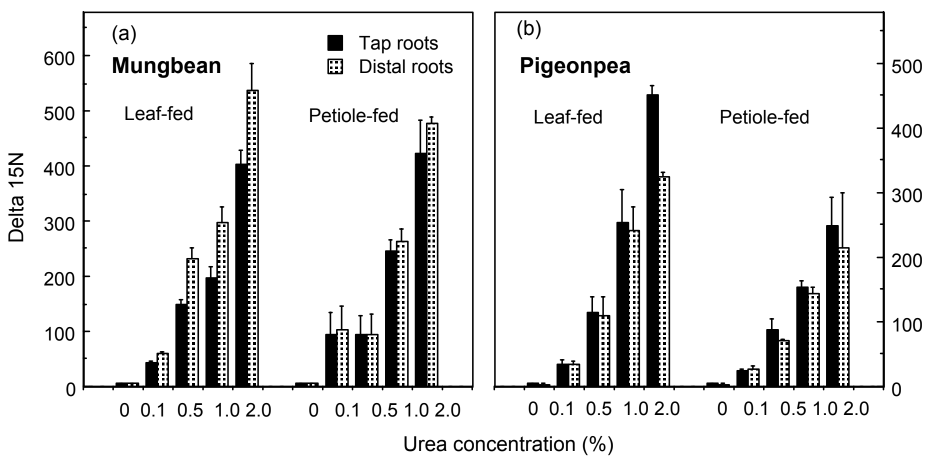

FIG. 2. The effects of urea concentration used for leaf-flap or petiole-feeding of (a) mung bean and (b) pigeon pea on the ^{15}N enrichment of the tap and distal roots. Error bars indicate ± standard error of the mean.

Reasonable amounts of root material were recovered from the potting medium for all species. For faba bean, chickpea and mung bean, recovered roots were, on average, 9 to 11% of total plant (shoot + roots) dry weight; recovered roots of pigeon pea, on the other hand, were 28% of total plant dry weight.

Nitrogen-15 analyses indicated substantial enrichments both for taproots (root crown, taproots and major laterals) and for distal roots for all concentrations of urea (Figs. 1 and 2). Root ^{15}N increased with increasing concentration of urea. Variability tended to be highest with the higher urea concentrations, most likely reflecting tissue damage and associated reduction in urea-solution uptake. The distal roots had consistently higher enrichments than taproots for faba bean, chickpea and mung bean, but not for pigeon pea.

With mung bean and pigeon pea, leaf-flap feeding enriched the roots more than did petiole feeding (Fig. 2). This was a slightly disappointing result because petiole feeding was technically simpler than feeding via the leaf flap and would have been the more attractive option for future studies.

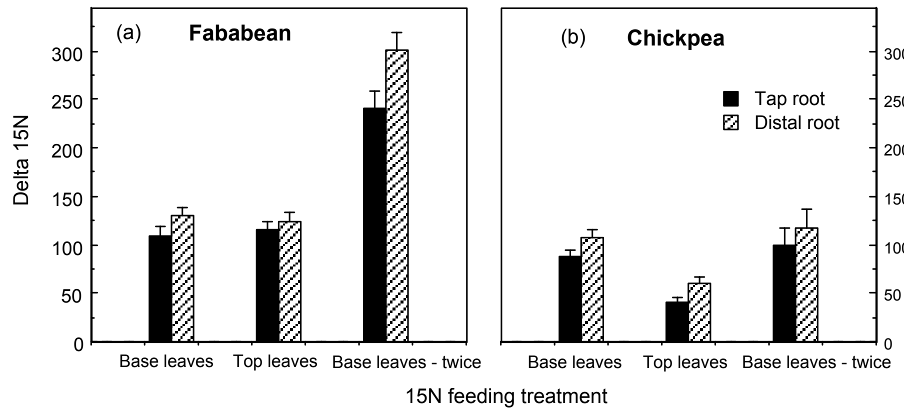

FIG. 3. The effects of leaf position and multiple feeding on the N enrichment of (a) faba bean and (b) chickpea tap and distal roots. Error bars indicate ± standard error of the mean.

3.2. Experiment 3: The effect of leaf position and multiple feeding on ^{15}N enrichment of roots

With faba bean, there was no effect of fed-leaf position on the ^{15}N enrichment of the roots (Fig. 3a). With chickpea, on the other hand, roots were more highly enriched when the leaves at the base of the stem were fed (Fig. 3b). With both species, a second ^{15}N application increased root enrichment, although the effect was marginal for chickpea. With all treatment/species combinations, the distal roots were again more highly enriched than the taproots.

3.3. Experiment 4: Comparison of the uniformity and distribution of ^{15}N in above- and below-ground plant parts

Uniformity of ^{15}N-labelling was further examined in this experiment (Fig. 4). Within the shoot, ^{15}N enrichments were highest in the lower part and lowest in the top section. There were no consistent differences between leaves and stems. In six of the nine comparisons, fruit enrichments were lower than those of leaves and stems.

The most striking outcomes of the belowground partitioning were the differences in enrichment of nodulated roots, unnodulated roots, and nodules. The two chickpea cultivars gave consistent results. For faba bean, the relative enrichment values were nodulated taproots (100), nodulated distal roots (100), unnodulated taproots (112) and nodules (62); average values for the two chickpea cultivars were nodulated taproots (100), nodulated distal roots (111), unnodulated taproots (156) and nodules (63).

4. DISCUSSION

Major criteria for ^{15}N-labelling of legumes to determine BGN are that:

- The method of ^{15}N feeding is relatively rapid and convenient, and has no deleterious effects on the plant.
- The ^{15}N fed to the shoot is translocated throughout the plant to enrich both aboveground and belowground parts.
- The roots are uniformly labelled with ^{15}N.
- The ^{15}N in the root-zone soil is derived only from the roots and nodules.
- The enrichment of root-derived N in the soil is also uniform and has the same enrichment as that of recovered roots.
- Enrichment in recovered plant parts and in the soil is sufficiently high for isotopic analysis.

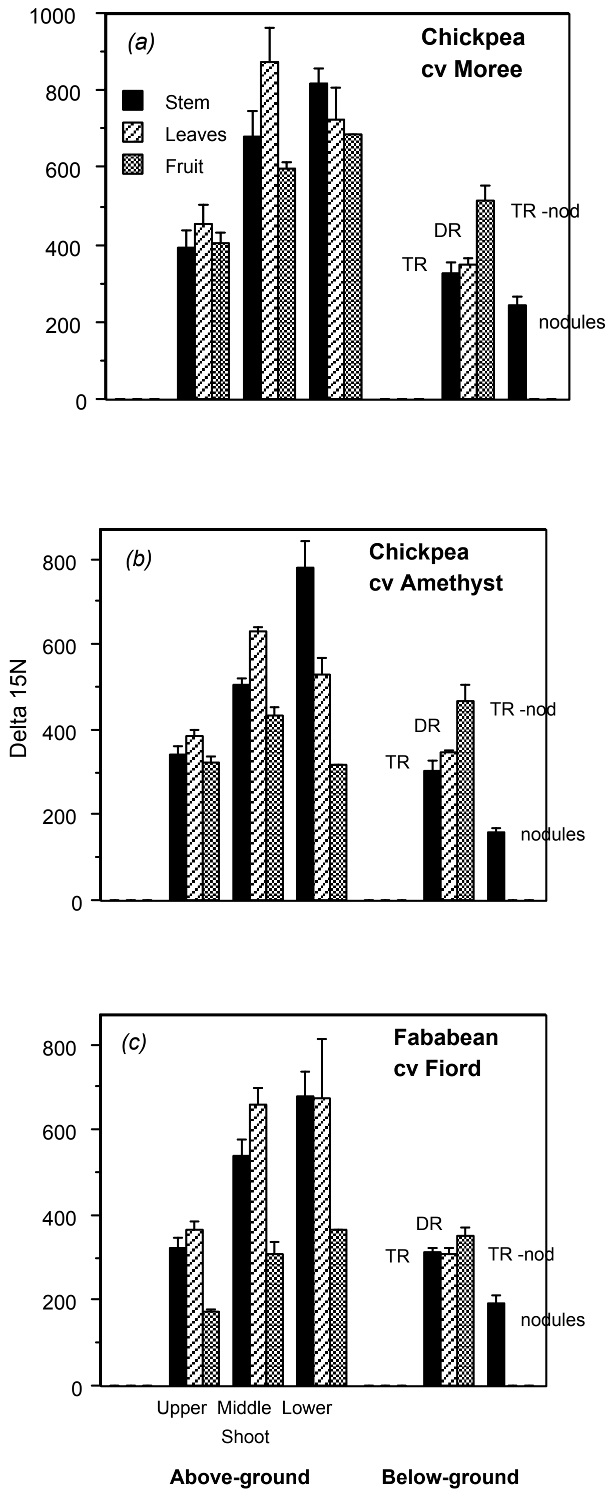

FIG. 4. The N enrichment of above-ground or below-ground components of nodulated faba bean and chickpea. TR indicates taproot (with nodules intact); DR indicates distal roots (with nodules intact); TR-nod indicates taproot with nodules removed.

With these requirements in mind, the procedures for ^{15}N shoot-labelling of the four target legumes were examined in the experiments reported in this paper. The optimal urea concentration of 0.5% was a compromise between securing a sufficiently high level of enrichment, whilst minimizing tissue damage. McNeill et al. [5,10] used 0.25 and 0.4% ^{15}N-urea solutions for labelling pasture-legume species, whereas Rochester et al. [11] used a 0.9% solution for the ^{15}N labelling of field-grown soybean. The small volume (0.2 mL) of urea used in our studies, compared to the 1.0-mL volumes in the pasture legume and soybean studies, was an attempt to decrease the duration of feeding. Thus, feeding was completed overnight, rather than over 2 or 3 days [5,11] or 2 weeks [10]. The results of Experiment 3 showed that root enrichment could be increased with multiple applications of ^{15}N. To counter the small volumes of fed urea, multiple feedings of ^{15}N will most likely be necessary for sufficiently high levels of plant enrichment.

Uniformity of ^{15}N enrichment was examined by Janzen and Bruinsma [6] for shoots, and by Zebarth et al. [9], Russell and Fillery [1,2] and McNeill et al. [5] for roots as well as shoots. Janzen and Bruinsma [6] reported uniform enrichments of senescent leaves, green leaves, grain heads and stems of labelled wheat plants. Enrichments of recovered roots were consistently lower, however, by a factor of 2 to 3 in solution-cultured plants and 1.5 to 2 in soil-grown plants. They did not separate the roots into distal and taproot fractions, and had no basis for questioning the assumption underlying the calculation of rhizosphere N and deposition (i.e. non-recovered, root-derived N in soil) that enrichment of all root-derived N is the same.

Russell and Fillery [1] compared the distribution ratios (% recovered ^{15}N/% total N) of different shoot fractions as well as of roots and nodules. They argued that the distribution ratio was a better indicator of the distribution of ^{15}N within the plant than atom% ^{15}N excess values. A ratio of 1.0 represented uniform distribution of ^{15}N, whilst <1.0 meant discrimination against ^{15}N and >1.0 a preference for ^{15}N. At final harvest of sand-cultured narrow-leafed lupin, distribution ratios were 1.0 for shoots and 0.8 for roots. Of more interest was the large difference between the ratios of roots and nodules, measured in a second, solution-culture experiment. Ratios were 1.1 for shoots, 1.3 for roots and 0.35 for nodules (average of two treatments). The overall ratio for the nodulated roots was 0.78.

Depletion of ^{15}N in nodules because of localized enrichment of fixed ^{14}N was the major reason for depletion of nodulated root ^{15}N. We considered that this would complicate the assessment of N fluxes from the belowground biomass. The large variation in enrichment within the root system also makes difficult the calculation of root-derived N in soil. With such differences in enrichment of nodules and root tissue, patterns of nodulation on the roots become critical. For the enrichment of recovered roots to be applied to the soil fraction, the ratio of nodule:root material in the soil fraction would need to be identical to the ratio of nodules:roots in recovered roots. Depending on the pattern of nodulation of the particular species (i.e. crown nodulation, lateral nodulation or evenly distributed nodulation) and on environmental influences on nodulation, this assumption may not always be met.

To address this potential problem, Russell and Fillery [2] sectioned the root-zone soil into layers and used the enrichment of recovered roots from each layer to calculate root-derived N in soil for that layer. Their data indicated that enrichments of recovered roots from the crown region (0.93 atom% ^{15}N excess, 0–8 cm depth) were substantially different from enrichments of lateral roots in the deeper (average of 1.67 atom% ^{15}N excess, 8–100 cm) layers. Enrichments of recovered roots in the four layers between 8 and 100 cm were reasonably uniform at 1.85 (8–20 cm), 1.69 (20–40 cm), 1.45 (40–60 cm) and 1.68 (60–100 cm).

In this study, enrichments of distal roots of faba bean, chickpea and mung bean were higher than for taproots. Pigeon pea was different, with taproot enrichment greater than distal-root enrichment. Experiment 4 showed clearly the effects of nodules on enrichment of nodulated roots. Faba-bean roots without nodules had 12% higher enrichment than faba-bean roots with nodules (Fig. 4). In the case of chickpea, unnodulated roots had 56% higher enrichment. The enrichment pattern for chickpea was similar to that reported for lupin [1].

Thus, the assumption that the enrichment of recovered roots is representative of enrichments of all root-derived N may not hold, particularly for species like chickpea. Simply applying the recovered-root enrichment to the unnodulated or even less-nodulated root-derived soil N will result in an overestimation of root N equivalents. Vertical sectioning of the root-zone soil so that root-derived soil N can be related to recovered roots in each section would be appropriate [2], but may be difficult in some situations, e.g. when plants are growing in heavy clay soils in the field. An alternative approach in those situations could be to assume predominately crown nodulation of the plants. Thus, recovered roots would be nodulated; root-derived N in soil would be without nodules. The ratios of nodulated root to unnodulated root enrichments above would then be used as an adjustement in the calculations.

ACKNOWLEDGMENTS

The research presented in this paper would not have been possible without the resources provided by various agencies (NSW Agriculture, CSIRO, University of Melbourne) and external funding via the John Allwright Fellowship and ACIAR (Australian Centre for International Agricultural Research).

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NITROGEN DYNAMICS AND FERTILIZER NITROGEN USE EFFICIENCY IN RICE FOLLOWING STRAW INCORPORATION AND WINTER FLOODING

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Abstract

Incorporation of rice (*Oryza sativa* L.) straw affects soil N supply by changing N and C inputs when compared with burning. This study was conducted to determine the effects of alternative rice straw management and winter flooding on seasonal N uptake, ^{15}N fertilizer use efficiency, and crop uptake of straw ^{15}N. Nitrogen-15 microplots were established at two sites, Maxwell and Biggs, by applying ^{15}N-labelled fertilizer during year four of a long-term rice straw management study. At the end of year four, ^{15}N-labelled straw was applied to assess uptake of straw-N in the following season. Zero-N fertilizer plots were established to calculate fertilizer-N recovery/use efficiency by the N difference method (FUE-ND). Fertilizer use efficiency calculated by ^{15}N dilution (FUE-^{15}N) over the growing season at Maxwell and at final harvest at Biggs was significantly higher when straw was burned rather than incorporated. Fertilizer use efficiency-ND was significantly greater than FUE-^{15}N, indicating a strong apparent added-N interaction (ANI). Straw management did not significantly affect the uptake of fertilizer ^{15}N or of straw ^{15}N in the second year. Winter flooding had no significant effect on any of the measured parameters. While increasing the total plant-available soil N supply, straw incorporation did not affect the total amount of ^{15}N fertilizer recovered after two growing seasons (average 43% in crop and in the 0–15 cm depth soil). This suggests that changes in labile soil N pools following adaptations in straw-management practices control soil N supply power without any changes in total soil N.

1. INTRODUCTION

Nitrogen is the most important nutrient in rice systems, accounting for 67% of total fertilizer applications to rice worldwide [1]. Nitrogen-uptake patterns in rice over the growing season depend on the availability from soil and fertilizer N [2,3]. When fertilizer N is applied pre-plant, its uptake tends to be concentrated toward the beginning of the season with soil N being the dominant N pool after the fertilizer N supply is depleted or immobilized [2]. A decline in total plant N content at maturity has been noted in some cases [4,5], possibly due to volatilization of NH_3 or senescence of leaves. The relationship of fertilizer N uptake to total N uptake over the growing season depends on timing of the fertilizer N application [4], and the amount of fertilizer N available [2]. The introduction of rice straw management, such as straw incorporation, often confounds these established relationships and requires additional research to elucidate the factors controlling N availability in rice.

Air and soil quality issues have increased the importance of alternative rice straw management practices in recent years. While burning is the traditional method of disposal of straw and stubble in temperate and tropical rice-growing areas [6,7], this practice is causing concern because of potential air pollution [8,9]. California legislation now restricts burning to less than 25% of the rice acreage, and allowable burning will decrease to zero. Alternatives to burning include soil incorporation or baling of the straw. Shallow flooding of fallow rice fields is common in California because of its potential to enhance decomposition of straw [10] and to provide winter wetland habitats for migrating waterfowl [11].

Addition of straw can increase soil organic matter content in rice systems [12]. In the long term, straw incorporation has resulted in increased N mineralization potential in non-rice and rice systems [13]. Sustained increases have been reported in microbial biomass following many seasons of straw incorporation compared to burning [14,15]. Incorporation of straw with a high C:N ratio initially immobilizes nutrients, including N, because nutrients are required to produce microbial biomass and stable soil organic matter. The N in the straw is also available to the microbial population, and after an initial equilibration period that may last up to 3 years following rice straw incorporation [12], plant available N supply in the soil tends to increase [13].

Table I. Soil characteristics at the Maxwell and Biggs sites at initiation of the long-term experiment on alternative rice straw management practices

Property	Maxwell	Biggs
	Willows clay: Fine, smetitic, superactive, thermic, Sodic Endoaquert, sodic >15SAR at depths to 1 m	Neerdobe clay: Fine mixed, super-active, thermic, Xeric Duraquert duripan variable : Neerdobe-Esquon complex at site
Physical		
Soil texture (g kg^{-1})		
Sand	50	170
Clay	510	350
Chemical		
pH	6.6	4.7
CEC (cmol kg^{-1})	42	30
Total C (g kg^{-1})	19.5	12.3
Total N (g kg^{-1})	1.7	1.0
Avail. P-Olsen (mg kg^{-1})	11.3	11.1
Exch. K (mg kg^{-1})	305	72
S (mg kg^{-1})	159	63
Ca (cmol kg^{-1})	0.16	0.12
Mg (cmol kg^{-1})	0.21	0.10
EC (S m^{-1})	0.14	0.04
SAR	7.8	<1.0
Na (cmol kg^{-1})	1.02	0.09

Studies on the impact of winter flooding on N dynamics in temperate rice systems have been lacking. However, the main effects of winter flooding may be due to increased straw decomposition, resulting from waterfowl activity [16], and to the effects of increased anaerobic conditions. The extended anaerobic time period during winter flooding increased extractable inorganic N [17] after 4 years compared to fallow flooding, possibly due to the less immobilization of N after incorporation of straw in anaerobic systems compared to aerobic systems [18]. The extended anaerobic time period during winter flooding may increase N availability to plants. Both winter flooding and higher C inputs have been reported to increase microbial respiration rates and affect microbial community structure [19,20].

Although studies have found that incorporation of straw can increase soil N supply to rice, the impact in temperate rice systems is not well understood. Additionally, the effect of these soil N supply changes on N use efficiency and seasonal uptake has not been examined. The objective of this study was to determine the impact of straw incorporation or removal and winter flooding on seasonal ^{15}N uptake and fertilizer N use efficiency (^{15}N and N difference methods). The fate of ^{15}N-labelled fertilizer in the second growing season and use efficiency of ^{15}N straw were also examined.

2. MATERIALS AND METHODS

2.1. Field sites

Straw and winter-flooding treatments were established at two sites in the Sacramento Valley of northern California. A 28-ha study site near Maxwell, Colusa County, was established in the fall of

1993. A 10-ha site at the California Rice Research Station near Biggs, Butte County, was established in the fall of 1994. Plot sizes at Maxwell and at Biggs were 42×180 m and 15×142 m, respectively. Main differences in soil characteristics between the two sites are lower clay content, pH, and exchangeable K at Biggs (Table I).

Treatments were arranged in a randomized complete block design incorporating straw-management practices in a split-plot design within main-plot treatments of winter flooding and no winter flooding. Treatments were replicated four times. The straw-management treatments were baling and removal, rolling, incorporation, or straw burning. Only two straw-management practices, burning and incorporation, were addressed in this portion of the study. Rice variety M202 was aerially seeded each spring onto fields that had been flooded approximately 1 day prior. The fields remained flooded throughout the growing season until crop maturity, and then were drained to allow drying for harvest. Straw treatments were applied in the fall, and winter flooded plots were flooded at 5 to 15 cm depth from November until drainage in March.

In the spring of the fourth growing season, 1997 at Maxwell and 1998 at Biggs, ^{15}N microplots were established. They were rectangular, 3×4 m, at Maxwell and circular, 2 m in diameter, at Biggs. Nitrogen-15 labelled urea at a rate of 20 kg N ha^{-1} at 10 atom% ^{15}N was applied just prior to pre-plant flooding. Additional unlabelled fertilizer N was applied as aqueous NH_3 and $NH_4H_2PO_4$ to obtain a total rate of 188 kg N ha^{-1} with an ^{15}N content of 1.07 atom%^{15}N at Maxwell. To reduce denitrification a nitrification inhibitor [N-serve 24E, nitrapyrin: 2-chloro-6-(tricholoromethyl) pyridine, Dow Elanco, Indianapolis, IN], was applied at a rate of 0.4 L ha^{-1}. At Biggs 161 kg N ha^{-1} as $(NH_4)_2SO_4$ with an enrichment of 1.24 atom%^{15}N was applied. To prevent lateral movement of the labelled ^{15}N, metal barriers were inserted into the soil around the microplots to a depth of approximately 15 cm.

During each year of the study, additional microplots within each main plot received no fertilizer N. Phosphorus was applied as triple superphosphate at the same rate as in the N fertilized plots, 74 and 57 kg P_2O_5 ha^{-1}, at Maxwell (1997) and Biggs (1998), respectively. These zero N-fertilizer plots were placed in a different location within the larger plot each year.

Following harvest of the ^{15}N-labelled crop at Maxwell in 1997, the straw from the ^{15}N-microplots in the burned treatments was transferred onto new ^{15}N-microplots in the straw-incorporated treatments. The ^{15}N-labelled straw from the burned treatment was replaced with surrounding unlabelled straw, which was subsequently burned. From the ^{15}N-microplots established in the fall of 1997, the contribution to the subsequent crop of ^{15}N-labelled surface straw, designated aboveground, as compared to the soil/root N and unburned stubble N, designated belowground, could be measured. Characteristics of the ^{15}N-labelled straw applied to the new ^{15}N-microplots are summarized in Table II.

Table II. Characteristics of ^{15}N-labelled straw applied in the autumn of 1997, Maxwell[a]

Characteristic	Winter flooded	Non-winter flooded
Total N (kg ha^{-1})	49.7 (4.0)[b]	52.5 (2.0)
Total C (t ha^{-1})	3.41 (0.21)	3.82 (0.21)
Atom % excess ^{15}N	0.449 (0.032)	0.419 (0.013)
C:N ratio	69.0 (2.7)	72.8 (2.1)
%N	0.58 (0.02)	0.53 (0.01)

[a]Straw was removed from the straw-burn treatment microplots and placed onto new microplots in the incorporated treatment.
[b]Standard error of the mean of four replicates.

The rate of ^{15}N straw applied was equal to the amount produced under straw-incorporated conditions. In the second growing season, the ^{15}N uptake in the ^{15}N-microplots established in the spring of the first year represented the uptake of the previous year's fertilizer N application from both soil N pools and aboveground and belowground residue. Fertilizer ^{15}N uptake in the second year through belowground N sources was calculated from the difference between ^{15}N uptake in the fertilizer ^{15}N microplots and ^{15}N uptake where only ^{15}N-labelled straw was applied.

2.2. Plant samples

Plant samples were collected throughout the growing season at Maxwell, with sampling dates concentrated toward the beginning of the season during rapid growth. Samples were collected at plant maturity and final harvest at Biggs. Five or more ^{15}N-labelled plants were selected at random and harvested, by carefully removal with roots, at each sampling time. A quadrat in the surrounding area was used for yield determination. The plants were washed to remove soil from roots, separated into roots, shoots, and panicles (when present), dried at 60°C, weighed and ground to a powder in a ball mill. The ^{15}N-labelled plants were then analysed for the concentration of N and atom% ^{15}N using a combustion continuous-flow isotope-ratio mass spectrometer (PDZ Europa Ltd., Crewe, England).

At final harvest, shoots were collected by cutting plants just above ground level. Total biomass and grain yield (1 m^2) were determined both from inside and from outside the ^{15}N microplot. There were no significant differences between yield estimates from the ^{15}N microplots and the main plots at Maxwell. However, yield was significantly affected by microplots and deemed unreliable at Biggs, likely due to the small microplot size. Yields from the ^{15}N microplot were used for all ^{15}N microplot-related calculations at Maxwell in 1997. In 1998, the main plot yields were used since no ^{15}N yield samples were taken due to the lack of significant differences between main plot and ^{15}N yields in 1997. At Biggs, yields from the main plot were used in calculations of total N uptake and FUE-^{15}N. Yields from the main plot and zero N-fertilizer microplot were used for calculating FUE-ND.

Plants from the final harvest were separated into grain and straw components, dried at 60°C and weighed. All grain yields are expressed at moisture content of 140 g kg^{-1}. The ^{15}N-labelled samples were first ground in a Wiley mill, ball milled for analysis, and analysed for %N and atom% ^{15}N as described above.

2.3. Soil samples

Soil samples were taken from the ^{15}N microplots to a depth of 15 cm throughout the study period. See Bird et al. [16] for analysis description of the soil N determinations. The results from the plant and soil ^{15}N analyses at the end of the second cropping season at Maxwell were used to prepare a budget of the ^{15}N fertilizer applied in the spring of 1997.

2.4. Fertilizer N use efficiency

Fertilizer use efficiency by the ^{15}N dilution method (FUE-^{15}N) was calculated as follows:

$$FUE{-}^{15}N = \frac{atom\%^{15}N\ excess_{plant}}{atom\%^{15}N\ excess_{fertilizer}} \times \frac{N_{plant}}{N_{fertilizer}} \times 100 \quad (1)$$

where

atom%^{15}N $excess_{plant}$ is atom % ^{15}N excess (over background levels) in the plant,
atom%^{15}N $excess_{fertilizer}$ is atom % ^{15}N excess in the labelled fertilizer N,
N_{plant} is total plant N (kg ha^{-1}),
$N_{fertilizer}$ is fertilizer N applied (kg ha^{-1}).

Straw N use efficiency, the proportion of the straw N that ended up in the crop the following year, was calculated as follows:

$$straw\,N\ use\ efficiency\ (\%) = \frac{atom\%^{15}N\ excess_{plant}}{atom\%^{15}N\ excess_{straw}} \times \frac{N_{plant}}{N_{straw}} \times 100 \qquad (2)$$

where

$atom\%^{15}N\ excess_{plant}$ is atom % ^{15}N excess (over background levels) in the plant,
$atom\%^{15}N\ excess_{straw}$ is atom % ^{15}N excess in the labelled straw,
N_{plant} is total plant N (kg ha^{-1}),
N_{straw} is total straw N applied (kg ha^{-1}).

Fertilizer N use efficiency by the N difference method (FUE-ND) was calculated as follows:

$$FUE - ND = \frac{NPlant_{fert} - NPlant_{zeroN}}{NFert} \times 100 \qquad (3)$$

where

$NPlant_{fert}$ is total plant N uptake in N fertilized plots (kg ha^{-1}),
$NPlant_{zeroN}$ is total plant N uptake in zero N plots (kg ha^{-1}),
N_{fert} is fertilizer N applied (kg ha^{-1}).

Interactions between added fertilizer N and native soil N that change the N content in a given pool are called added N interactions (ANIs) [21]. These interactions may result in different estimates for FUE-^{15}N and FUE-ND.

2.5.Statistical analysis

Data were analyzed using the PROC GLM procedure of SAS [22]. Analysis of variance (ANOVA) was used to determine treatment effects and the "flood*block" MSE was used as the error term for winter flooding. Repeated measures ANOVA was used to determine treatment effects over time during the growing season.

3. RESULTS

Neither straw management nor winter flooding significantly affected grain and straw yields. Grain yields at Maxwell averaged 13.1 t ha^{-1} and 10.9 t ha^{-1} in 1997 and 1998, respectively, and grain yield at Biggs averaged 8.4 t ha^{-1} in 1998, significantly lower than at Maxwell in the same year ($P < 0.001$). The average straw yields at Maxwell were 9.4 t ha^{-1} and 8.1 t ha^{-1} in 1997 and 1998, and the average straw yield at Biggs in 1998 was 7.4 t ha^{-1}, again significantly lower than at Maxwell ($P < 0.01$).

Plant N uptake over the growing season at Maxwell reached a maximum between 60 and 80 days after seeding in 1997 and 1998 (Fig. 1). In 1997, there were no straw management or winter flooding effects on total N uptake over the growing season, but in 1998 the incorporation of straw significantly increased crop N uptake when analysed over the entire growing season ($P < 0.01$). By final harvest, straw incorporation significantly increased total N uptake at normal N fertilization levels in 1998 (Table III) and without N fertilizer application in 1997 and 1998 [23].

As with total N uptake, fertilizer N uptake at Maxwell peaked at 60 to 80 days after seeding, reaching a maximum FUE-^{15}N values during the season of 37% and 32% when straw was burned or incorporated, respectively (Fig. 2). Values for FUE-^{15}N over the season were significantly greater when straw was burned than when it was incorporated ($P < 0.05$). This trend was noted only in the grain at final harvest (Table III), and neither straw management nor winter flooding had a significant effect on total plant FUE-^{15}N at Maxwell (Fig. 3). While winter flooding again had no effect, straw management significantly affected fertilizer N uptake at Biggs (Table IV). The FUE-^{15}N at Biggs averaged 31% when straw was burned and 24% when it was incorporated ($P<0.01$) (Fig. 4).

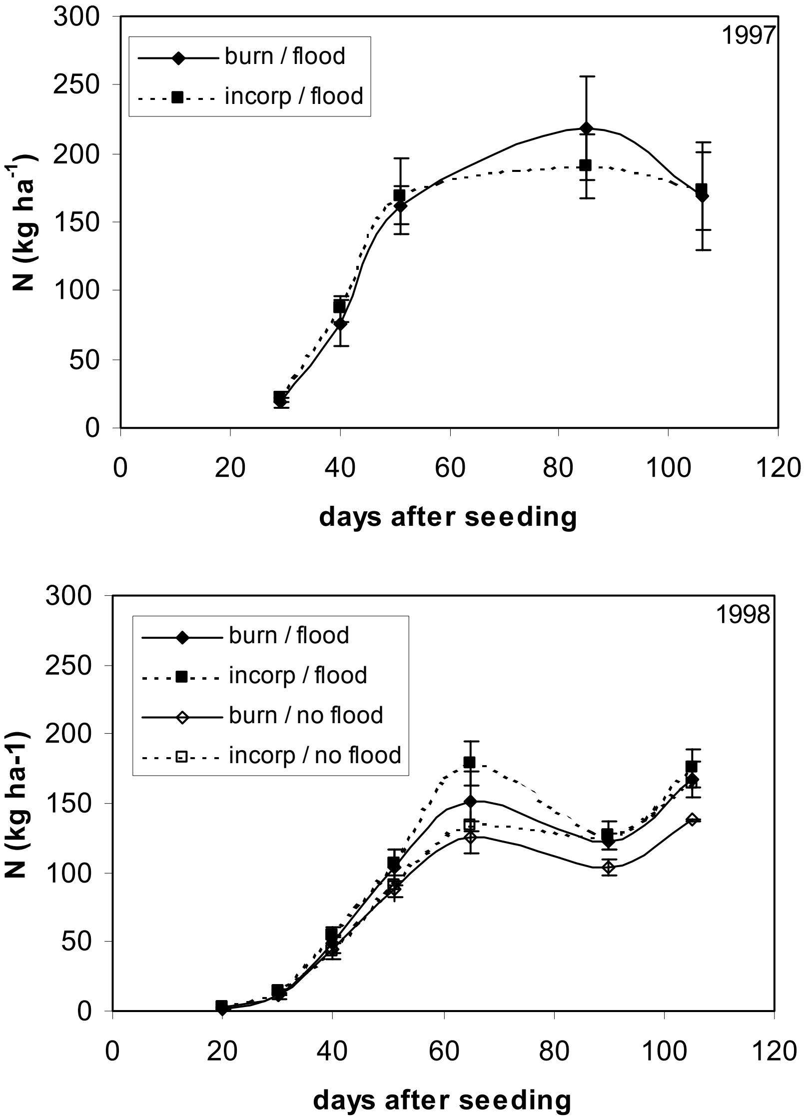

FIG. 1. Total plant N uptake at Maxwell over growing seasons 1997 and 1998. Bars are standard error of four replicates.

Fertilizer use efficiency-ND was on average 1.7 and 1.5 times greater than FUE-^{15}N at Maxwell and Biggs, respectively (Figs. 3 and 4). This indicated the presence of an ANI, where fertilizer N uptake, as measured indirectly, was greater than that measured directly by the ^{15}N method. There were no treatment effects at either location for FUE-ND when the total plant was considered, although FUE-ND for the grain-N at Maxwell was greater when straw was burned compared to straw incorporation ($P < 0.05$, data not shown). The difference in FUE-^{15}N due to straw management was also more pronounced in the grain than in the straw both at Maxwell and at Biggs. The difference in fertilizer-N recovery between FUE-ND and FUE-^{15}N (the ANI) at Maxwell in 1997 corresponded to 49.0 kg N ha^{-1}.

In the second growing season at Maxwell, an average of 2.3% of the ^{15}N-fertilizer applied the previous year was accumulated by rice at maturity (Fig. 5). By final harvest, 3.0% of the previous year's fertilizer was in aboveground plant parts (data not shown). The majority of the labelled ^{15}N uptake was from belowground sources rather than aboveground straw (Fig. 5A versus Fig. 5B). Slightly greater uptake of ^{15}N fertilizer in grain was seen in incorporated compared with burned plots ($P=0.078$) in the second year.

Table III. Soil and fertilizer N uptake at final harvest as affected by rice straw management and winter flooding, Maxwell 19 97 and 1998

Year/ Management	Grain			Straw			Total plant		
	Total N	Soil N	Fert N	Total N	Soil N	Fert N	Total N	Soil N	Fert N
					(kg ha^{-1})				
1997									
Burn/winter flood	119 (9)[a]	69 (8)	50 (3)	50 (4)	28 (4)	21 (2)	169 (13)	97 (11)	72 (4)
Burn/non-winter flood	127 (6)	74 (4)	53 (2)	53 (2)	31 (1)	21 (1)	180 (7)	105 (5)	75 (3)
Incorporate/winter flood	128 (6)	79 (4)	49 (3)	67 (1)	42 (1)	25 (1)	195 (6)	121 (5)	74 (4)
Incorporate/non-winter flood	119 (11)	79 (10)	40 (3)	62 (8)	41 (7)	20 (2)	181 (19)	121 (17)	60 (6)
					Statistics				
Analysis of variance									
Straw	NS	NS	*[b]	**[c]	**	NS[d]	NS	NS	NS
Winter flood	NS	NS	NS	NS	NS	NS	NS	NS	NS
Straw×winter flood	NS	NS	NS	NS	NS	NS	NS	NS	NS
1998									
Burn/winter flood	96 (6)	–[e]	–	46 (4)	–	–	141 (5)	–	–
Burn/non-winter flood	96 (5)	–	–	51 (2)	–	–	147 (6)	–	–
Incorporate/winter flood	115 (10)	–	–	59 (2)	–	–	174 (13)	–	–
Incorporate/non-winter flood	103 (2)	–	–	57 (4)	–	–	160 (4)	–	–
					Statistics				
Analysis of Variance									
Straw	**	–	–	**	–	–	**	–	–
Winter flood	NS	–	–	NS	–	–	NS	–	–
Straw×winter flood	NS	–	–	NS	–	–	NS	–	–

[a]Standard error of the mean of four replicates. [b,c]Significant at the 0.1 and 0.05 probability levels, respectively. [d]Not significant. [e]Nitrogen-15-labeled fertilizer was applied in 1997 only, so total N uptake in 1998 was not divided into soil- and fertilizer-N components.

Although plant N uptake at final harvest was greater in incorporated versus burned treatments by 13.4 kg N ha^{-1} in 1997 and 22.8 kg N ha^{-1} in 1998, only 1.8 kg N ha^{-1} came directly from straw in 1998. Straw N inputs averaged 51 kg N ha^{-1}, resulting in straw N use efficiency of 3.5% in the aboveground portion of the plants. Of the straw N taken up, 0.8 kg ha^{-1} originated in the previous year's fertilizer N application. Straw N use efficiency (roots and shoots) increased over the growing season along with N uptake and the majority of the straw N was accumulated by 60 to 80 days after seeding (Fig. 6). There was no significant effect of winter flooding on straw N use efficiency.

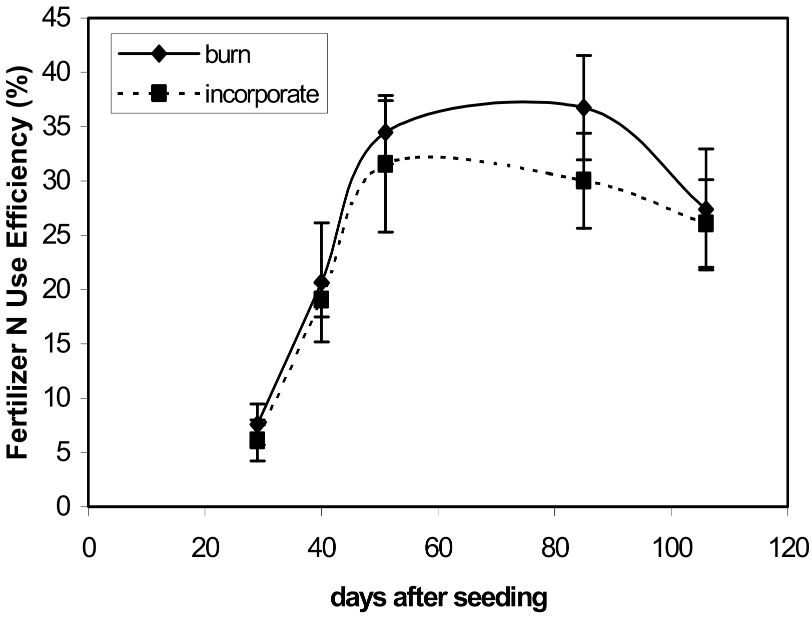

FIG. 2. Fertilizer N use efficiency over the growing season, Maxwell 1997. No significant straw effect for individual time points, but straw-management effect over time is significant at P <0.05.

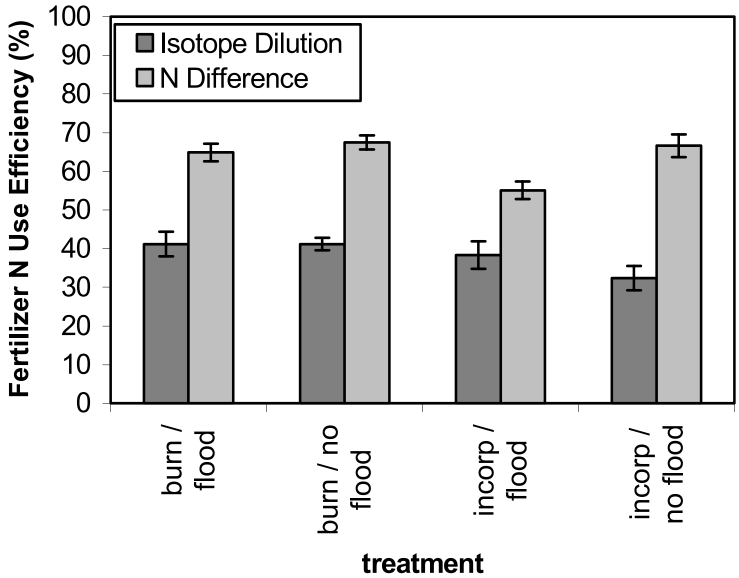

FIG. 3. Fertilizer N use efficiency in rice (final harvest) as affected by alternative straw management and winter flooding, Maxwell 1997. Comparison of ^{15}N-dilution and N-difference methods. No significant treatment effects for either method.

Total ^{15}N in plant pools was calculated at final harvest in 1997 and 1998 for Maxwell (Table V). Total ^{15}N in soil pools was determined from 1997–1998 [17] and values for crop maturity in season two (September 1998) are presented in Table V. Following harvest in 1997, up to 41% of the fertilizer N applied in the burned treatments was removed either through grain (30%) or by burning the straw (up to 11%). Only 24% of the fertilizer N applied was removed in the grain and none in the straw when the straw was incorporated. In spring 1998, total fertilizer ^{15}N recovery was higher where straw was incorporated rather than burned (P=0.054), although by fall 1998 and spring 1999 fertilizer N loss was similar among treatments [17].

Table IV. Total soil and fertilizer N uptake at final harvest as affected by rice straw management and winter flooding, Biggs 1998

Management	Grain			Straw			Total plant		
	Total N	Soil N	Fert N	Total N	Soil N	Fert N	Total N	Soil N	Fert N
	(kg ha^{-1})								
Burn/winter flood	72	41	31	41	22	19	113	64	49
	(5)[a]	(3)	(2)	(8)	(4)	(4)	(12)	(7)	(5)
Burn/non-winter flood	75	43	33	42	23	19	117	65	52
	(2)	(6)	(1)	(4)	(3)	(2)	(6)	(6)	(3)
Incorporate/winter flood	70	47	22	40	26	14	110	73	37
	(7)	(8)	(1)	(4)	(3)	(1)	(10)	(9)	(1)
incorporate/non-winter flood	69	44	25	42	26	16	111	71	41
	(8)	(4)	(4)	(6)	(5)	(1)	(18)	(13)	(2)
				Statistics					
Analysis of variance									
Straw	NS[d]	NS	**[c]	NS	*[b]	*	NS	NS	**
Winter flood	NS	NS	NS	NS	NS	NS	NS	NS	NS
Straw×winter flood	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Standard error of the mean of four replicates. [b,c]Significant at 0.1 and 0.01 probability levels, respectively. [d]Not significant.

Fertilizer ^{15}N in plant pools at harvest at the Biggs site was also assessed (Table VI). There was a stronger effect of straw management on fertilizer ^{15}N uptake in both the grain and the straw. Due to low ^{15}N label in the straw and the small size of the microplots, the residual ^{15}N uptake in the second year after fertilizer ^{15}N application was not examined.

4. DISCUSSION

4.1. Yield and N accumulation

After 5 years of rice-straw incorporation, there were no significant differences in grain yield compared to the burned treatments. Nitrogen fertility played a strong role, and the positive yield response to straw incorporation was dependent on the level of N fertilization. The highest increase in grain yield due to straw incorporation (up to 100%) was observed when no N fertilizer was applied [23]. However, no significant differences in grain yield between straw-management practices were observed when N was applied at recommended rates. This lack of response indicates that fertilizer-N rates can be reduced when straw is incorporated [23].

Earlier work in California found no significant yield differences between incorporation and burning of straw after 5 years [7], although the effect of straw incorporation seemed to be dependent on N content of the straw [24]. However, increased nutrient availability was reported following long-term incorporation of rice straw in tropical regions [9,12], resulting in reduced fertilizer N requirements and/or increased crop yields. In this study the increased plant N uptake following straw incorporation indicates an increase in plant-available soil N (Table III). The increase in plant-available N could be due to the greater amount of N in the labile soil organic matter pools [14] or to promotion of microbial activity following addition of organic matter [8,17].

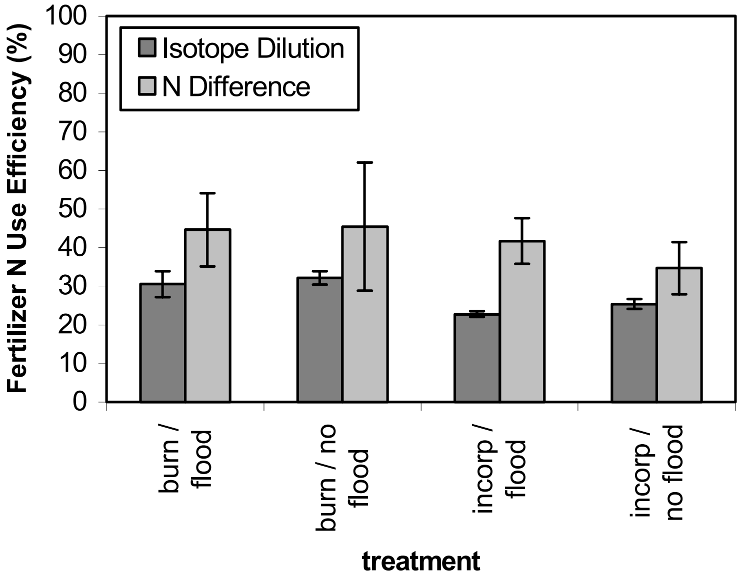

FIG. 4. Fertilizer N use efficiency in rice (final harvest) as affected by alternative straw management and winter flooding, Biggs 1998. Comparison of ^{15}N-dilution and N-difference methods.

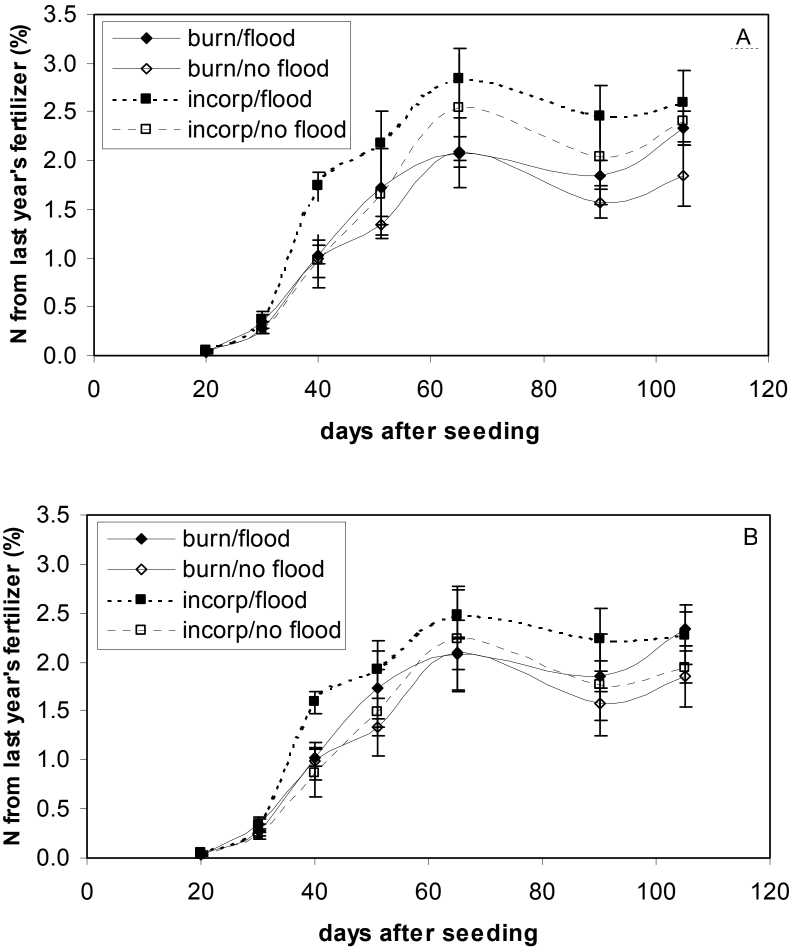

FIG. 5. Residual fertilizer N uptake as affected by alternative straw management practices and winter flooding, Maxwell 1998. Fertilizer N applied previous year. A. Includes all aboveground and belowground sources of N from previous year's fertilizer. B. Includes only the N through belowground pools (N through residue excluded).

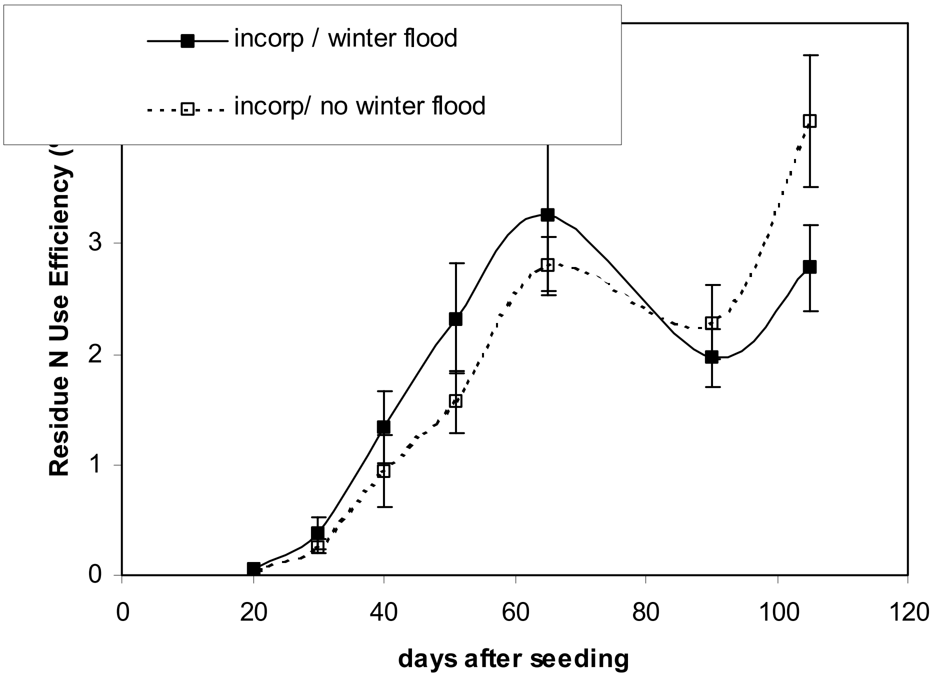

FIG. 6. Residue N use efficiency in rice over the growing season as affected by winter flooding, Maxwell 1998. Bars are standard error of four replicates.

Table V. The ^{15}N in plant (1997 and 1998) and soil pools (1998) as affected by straw management and winter flooding, Maxwell

Year/ Pool	Burn/winter flood	Burn/no winter flood	Incorp/ winter flood	Incorp/ no winter flood	Analysis of variance		
	(% of total fertilizer N applied in spring 1997)				Straw	Winter flood	Straw×winter flood
Harvest 1997							
Grain[a]	27	28	26	21	*[b]	NS[c]	NS
Straw	12	11	13	11	NS	NS	NS
Harvest 1998							
Grain	1.6	1.9	2.9	2.0	*	NS	NS
Straw	0.90	0.70	1.1	0.90	NS	NS	NS
Soil (0–15 cm)	14	15	17	14	NS	NS	NS
TOTAL	16	17	21	16	NS	NS	NS
Lost from system	57	54	53	63	NS	NS	NS

[a]Nitrogen in the grain is removed at harvest, and N in the burned straw is also lost.
[b]Significant at the 0.10 probability level. [c]Not significant.

Table VI. The ^{15}N in plant pools as affected by straw management and winter flooding, Biggs 1998

Year/ Pool	Burn/winter flood	Burn/no winter flood	Incorp/winter flood	Incorp/no winter flood	Analysis of variance		
	(% of total fertilizer N applied in spring 1998)				Straw	Winter flood	Straw× winter flood
Harvest 1998							
Grain[a]	19	20	14	16	***[c]	NS[d]	NS
Straw	12	12	8.8	9.9	*[b]	NS	NS

[a]Nitrogen in the grain is removed at harvest, and N in the burned straw is also lost.
[b,c]Significant at the 0.1 and 0.01 probability levels, respectively. [d]Not significant.

Total plant N and fertilizer N uptake reached maximum values at 60 to 80 days after seeding at Maxwell in both years. This is the time of maximum tillering and panicle initiation. Patrick and Reddy [25] also found a large portion of fertilizer N uptake occurred early in the season. Other studies found N uptake to continue until much later in the growing season [2,4]. This discrepancy in timing of maximum N uptake may be due to differences in soil N availability over the growing season, use of different rice varieties, climatic differences, or length of growing season. In the current study, both total N and fertilizer N recovery dropped slightly toward the end of the season. Guindo et al. [4] also found a similar drop in total fertilizer N recovery and total plant N content using a pre-flood fertilizer N application. Split fertilizer N application has resulted in increasing total N and static fertilizer N content [2] or increased total plant N content [26] toward the end of the season.

The relationship of fertilizer N uptake to total N uptake in rice has been shown to be dependent on timing of fertilizer N application [3,25,27]. Improved timing and application techniques, such as split applications, can reduce losses and increase fertilizer N use efficiency. Later-maturing rice varieties also tend to accumulate more soil N versus fertilizer N than early-maturing rice, indicating that fertilizer N tends to be most available in the beginning of the season [27]. Microbial competition for fertilizer N may explain these observations. In our study, the rice variety, M202, is late maturing and this may explain the similar uptake patterns of soil and fertilizer N.

Incorporation of straw increased N uptake in N-fertilized plots by 10 and 23 kg N ha^{-1} at Maxwell in the fourth and fifth years of the study, respectively (Table III). The increase in N uptake due to straw incorporation in unfertilized plots was even more dramatic [23]. However, on average, only 3.5% of the straw N directly entered the following year's crop (Fig. 6). Therefore, the impact of straw incorporation on N availability is much larger than would be suggested from the recovery of one year's worth of straw-N in the subsequent crop. Additional benefits following the incorporation of organic material, such as mineralization of other nutrients and improved soil quality, may lead to an increase in total N accumulation in the crop by supplying other limiting nutrients and increasing microbial activity.

Although not statistically significant, there appeared to be some increase in N uptake caused by winter flooding in the incorporated treatments (Table III). In Bird et al. [17] we reported greater extractable inorganic N in winter flooded incorporated and burned plots compared to non flooded both prior and during the growing season. The lower N requirements for decomposition under anaerobic conditions compared to aerobic conditions [18] may have increased net N mineralization and consequently plant N uptake. Further, winter flooding effects on microbial community diversity and composition were detected during the winter flood period in the first two seasons of the field study [8,19].

4.2. Nitrogen-15 fertilizer use efficiency

The FUE-^{15}N values measured in this study are comparable to the 30 to 50% values reported in other research [28,29]. They tend to be lower than those reported for upland crops, which are also dependent on crop and soil type, production methods, and timing of fertilizer application [30]. Other studies have also reported that application of fertilizer N later in the growing season increases FUE-^{15}N [25], although Bronson et al. [28] did not notice any difference in FUE-^{15}N between split fertilizer applications with different times of application. Values of FUE-^{15}N have been noted in the 72 to 79% range when ^{15}N fertilizer was applied 27 and/or 55 days after emergence [3].

Due to substitution of labelled fertilizer ^{15}N atoms for unlabelled ^{14}N atoms in the soil, FUE-^{15}N is more affected by timing of fertilizer application than is FUE-ND [31]. Total losses from the soil-plant system are greater when N fertilizer is applied earlier in the season [25]. Therefore, lower fertilizer recovery of early-applied ^{15}N fertilizer may be a result of real fertilizer N losses, and not only due to mineralization/immobilization turnover in the soil.

The FUE-^{15}N was greater when straw was burned rather than incorporated (Figs. 3 and 4). Incorporation compared with burning of straw increased the N availability through an increase in net N mineralization and corresponding dilution of fertilizer ^{15}N. While there was an increase in soil N uptake by the crop when straw was incorporated, an increase in fertilizer N uptake was measured when straw was burned (Tables III and IV). Therefore, the rate of fertilizer N application may be reduced when straw is incorporated. After four and five seasons of straw incorporation in situ*,* greater N immobilization shortly after residue incorporation and greater N mineralization during the growing season were observed compared with burned [17]. Under laboratory conditions, the rate of gross N mineralization was greater in soil sampled prior to planting where straw had been incorporated rather than burned for 6 years (2.1 versus 1.4 μg N/g soil/day, P=0.057, unpublished data). Further, four seasons of residue incorporation increased the C and N contents of the active light and mobile humic fractions [14]. Clearly, the incorporation of straw for a prolonged period of time changed the overall N dynamics and cycling in the soil and caused a net increase in the N-supplying power of the soil reflected in higher yields and total N uptake of the unfertilized rice crop. Adjustment of fertilizer N application to better reflect soil N supply should be considered to increase fertilizer N use efficiency in rice systems [32].

4.3. Added N interactions

The recovery of fertilizer N varied widely, whether based on the ^{15}N-dilution or the N-difference method (Figs. 3 and 4). Such a large difference in the recovery of fertilizer-N indicates the strong presence of an ANI. The ANIs observed at Maxwell and Biggs could be apparent or real. An apparent ANI is caused by mineralization/immobilization turnover, in which newly mineralized unlabelled N replaces fertilizer ^{15}N ions in solution [21]. This process is microbially driven, with concomitant N immobilization of added fertilizer N and mineralization of native soil N. At the Maxwell site, a sustained, higher microbial biomass C and N pool was observed after year 4 along with greater N fertilizer recovered as labile humic N in incorporated plots compared with the burned [14,17]. These results suggest that the microbial stabilization of fertilizer N leads to the enhanced apparent ANI with incorporation compared to burned. An apparent ANI is also the most likely contributor when the ANI increases with a longer contact period between fertilizer N and the soil N pools [31]. Since the uptake curves for fertilizer N and total N were similar in shape (Figs. 1 and 2), fertilizer N and soil inorganic N are likely present in the same or similar pools, making pool substitution of labelled and unlabelled N probable [33]. It has been suggested that apparent ANIs likely constitute the majority of observed ANIs [21].

Studies using ^{15}N-labelled fertilizer in rice systems have often found positive ANIs [33], which, in tropical rice production systems at various times throughout the growing season, ranged from –7.0 to 23 kg N ha^{-1} [31]. The ANI increased where fertilizer N was in contact with the soil for a greater period of time. The degree of pool substitution, and thus the nature of the observed ANI, depends on method of fertilizer application [31]. The ANI measured at Biggs was estimated at 14 kg N ha^{-1} while at Maxwell values were much higher, i.e. 57 and 38 kg N ha^{-1} when straw was incorporated and burned, respectively. The higher ANIs at Maxwell might have been caused by higher organic matter content if associated with higher N turnover rates. Also, the greater yield response to fertilizer N at Maxwell could have resulted in a higher real ANI due to more root penetration or root exudates and turnover.

The FUE-^{15}N at Biggs was lower than at Maxwell, and can be partially explained by the poor growing season in 1998 (El Niño) compared to the better growing season in 1997 that had a warmer and dryer spring. However, differences in soil characteristics and management practices play a large role, since FUE-NDs from 1995 through 1998 were consistently lower at Biggs than at Maxwell (average of 43% at Biggs vs. 66% at Maxwell). The low soil extractable K at Biggs [10] may also have contributed to lower N use efficiencies.

4.4. Residual ^{15}N fertilizer

Tracing the fate of the ^{15}N-fertilizer through the second growing season indicated that belowground pools (root and microbial derived) are more significant sources of plant available N than incorporated straw. A significant amount of fertilizer ^{15}N that was immobilized in the soil after 1 year was available for crop uptake in the subsequent growing season. In the spring prior to the second growing season (May 1998), 21% of the original ^{15}N-labelled fertilizer was measured in the top 15 cm of the soil profile [17]. At final harvest, the crop had accumulated 15% of that ^{15}N (see Table V), compared to 41 and 35% of the fertilizer ^{15}N taken up the year before in burned and incorporated treatments, respectively. Therefore, as expected, by the second year the N added as fertilizer was in less-available forms.

In contrast, the incorporated straw alone contributed 3.5% of its total N, and 3.5% of the fertilizer-^{15}N within the residue, to the subsequent crop. Only 13% of the ^{15}N-labelled fertilizer in the second-year crop came from the rice residue. Therefore, the availability of the ^{15}N-residue and ^{15}N-soil pools appeared to be different and the belowground ^{15}N pools were more important N sources to the crop. Unfortunately, most other field studies have followed the fate of only ^{15}N-labelled aboveground crop residues [6] or combined roots and shoots [34]. A separation of aboveground versus belowground contributions as a source of N for the subsequent crop is seldom made. In addition, belowground sources of ^{15}N include root, crown, and microbially immobilized fertilizer N, making it difficult to assess the importance of these pools in the years following fertilizer addition. From our study it appears that in rice cropping systems the aboveground contribution may not be as important a source of N as belowground sources such as remaining fertilizer-^{15}N, belowground ^{15}N labelled residues (roots, exudates) or ^{15}N immobilized by microbial biomass during the year of fertilizer application. Nitrogen fractions including mobile humic substances, light fraction, and microbial biomass are the most active soil N pools, and likely contribute the majority of the ^{15}N-label to the second year crop [14,17].

While the straw N use efficiency was low, the cumulative effect after 4 and 5 years of straw incorporation on N nutrition was greater than direct N flow from straw to crop. Although only 1.8 kg N ha^{-1} of straw N was directly available to the crop in the year following incorporation, total N uptake increased by 10.2 kg N ha^{-1}. Therefore, these results, combined with the evidence that yield and N uptake only began to be affected by straw management by the third year of the long-term study [23], suggest that active N pools in incorporated plots were increasing over time, thereby enhancing available N more as incorporation practices continued.

Neither straw management nor winter flooding affected the total amount of ^{15}N fertilizer remaining in the system at Maxwell after two cropping seasons (Table V) [17], even though more fertilizer N was removed from the system where straw was burned, both in the grain and the burned straw. The low straw use efficiency may have been due to losses of the residue N following spring tillage over the growing season. This could contribute to the lack of difference between treatments both in ^{15}N plant uptake and total ^{15}N recovery.

4.5. Soil N availability

When FUE-^{15}N was calculated using the main-plot yields at Maxwell, the lower variability in the yield data led to significantly higher FUE-^{15}N where straw was burned rather than incorporated. The same trend was noticed from ^{15}N plot yields and in the FUE-^{15}N at Biggs (Table IV). In the second cropping season, residual ^{15}N fertilizer uptake as grain tended to be higher when residues were incorporated compared with burned. Moreover, N uptake in unfertilized rice after 4 and 5 years of straw management treatments increased significantly with straw retention. These trends suggest that incorporation of straw led to an overall increase in the plant-available soil N.

5. CONCLUSIONS

Straw management and winter flooding had no effects on rice grain yield, but N uptake increased when straw was incorporated for 5 years. Due to increased soil N availability as a result of straw incorporation, fertilizer N use efficiency declined when straw was incorporated compared to fertilizer N use efficiency when straw was burned. Therefore, in our study, fertilizer N rates can be reduced by at least 12 kg N ha^{-1} (the average amount of increase in N uptake) when straw is incorporated. A large difference in the FUE-^{15}N and the FUE-ND was observed, likely caused by a strong ANI whereby unlabelled N in the microbial biomass was substituted for ^{15}N-labelled fertilizer. Hence, the recovery of fertilizer by ^{15}N isotope underestimates the role of fertilizer N as a source of N for the rice crop, whereas the contribution of fertilizer-N to rice as determined by the N balance method was overestimated. The belowground pools were shown to be very important in the availability of N to rice, and the small uptake of straw N compared to a much higher effect of straw N indicates significant N cycling between various soil N pools.

ACKNOWLEDGMENTS

We thank the California Energy Commission, the California Rice Research Board and Ducks Unlimited for their generous financial support. We also thank the California Rice Research Station and Canal Farms for their collaboration and assistance in the field operations. The technical assistance of S. Scardaci, Dr. M. Hair, M. Llagas, P. Flaugher, P. Kong, S. Lo, and T. Kraus, the statistical assistance of Dr. F.C. Stevenson, and the valuable comments made by Dr. C.A. Beyrouty on an earlier version of the manuscript are highly appreciated.

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OPTIONS FOR SOIL ORGANIC CARBON MAINTENANCE UNDER INTENSIVE CROPPING IN THE WEST-AFRICAN SAVANNA

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Abstract

Data from the derived savanna zone in southern Benin indicated that some intensive cropping systems (maize/*Cajanus* and maize/*Mucuna* relays; maize/cotton with *Senna siamea* hedgerows) returned about 12 Mg DM ha^{-1} $year^{-1}$ of plant biomass to the soil. This compared favorably with the 8 Mg DM ha^{-1} $year^{-1}$ reported for current maize/cotton and maize/cowpea systems. Based on calculations with the Rothamsted carbon model, this extra biomass translates into an increase in the topsoil carbon content of 0.33% C after 20 years. These calculations were found to be in line with available data from long-term experiments in West Africa. While the relation between residue-input rates and soil organic carbon (SOC) buildup is reasonably well known, little is known about how this translates directly into yield benefits. As a way to identify the potential of such benefits, we translated achievable SOC gains into increases in top-soil CEC, pH-buffer capacity, and available water (AW) in the soil profile in relative terms, i.e. relative to the AW without additional SOC buildup, and relative to the CEC and pH-buffer capacity contributed by the mineral soil constituents. This indicated that achievable increases in AW from higher SOC contents are insignificant. Furthermore, we found that increases in CEC and pH-buffer capacity through SOC buildup can be justified only in a limited number of soils where the mineral fraction in the topsoil provides very little buffering. Finally, we used a response-curve approach to single out the various benefits from organic matter inputs and to look at interactions with mineral fertilizers. We also indicated the scope for a more mechanistic interpretation, focusing on the effect of increased pH buffering as a way to minimize losses from NH_3 volatilization with urea applications in poorly buffered soils.

1. INTRODUCTION

Low fertilizer efficiency in sub-Saharan Africa constitutes a major impediment for agricultural intensification [1]. Factors responsible for the low efficiency are unfavorable rainfall distribution, sub-optimal planting density, poor control of weeds and pests, and often also an imbalanced supply of macro- and micro-nutrients, a low nutrient- and/or water-holding capacity and the occurrence of Al/Mn toxicity. Currently, there is renewed interest in combining organic sources of nutrients with mineral fertilizers in order to redress some of the soil-related constraints. A positive interaction between both nutrient sources means that a farmer obtains a higher yield increase from a given quantity of mineral fertilizer when used in combination with organic materials instead of in isolation. So the quest for possible positive interactions (or added benefits) is, in fact, nothing else than trying to improve fertilizer efficiency through the organic component.

There are indications that added benefits from combining organic sources of plant nutrients with mineral fertilizer are absent in the short term [2] or are significant only under specific conditions [3–5]. The long-term benefits arising from the increased nutrient capital and increased buffer capacity for water and nutrients and against pH-changes may, however, be more important than the short-term benefits.

A clear example of strong benefits from organic amendments in the long run was found in a long-term experiment in Saria, Burkina Faso [6]. After 15 years, a response to application of NPK fertilizer alone was almost absent, while yields in the treatment with a combined application of farmyard manure and NPK fertilizer were effectively maintained over the years. Pichot et al. [6] concluded that the clear benefit of farmyard manure in the Saria experiment was due to its cation content together with the increase in CEC associated with soil organic matter (SOM) build-up. Potassium deficiencies and acidification from fertilizers could be counteracted in this way. This experiment illustrates a number of important features of many similar long-term experiments conducted in West Africa (see, e.g., [7–9]): first, the organic matter is often produced off-site, thus overemphasizing the effects of the nutrients applied with the organic matter. Secondly, application rates are often higher than what a farmer can apply, given the available quantity of manure or the amount of plant residues the farmer can produce in situ. Thirdly, it is often impossible to know to what extent the observed benefits or interactions are due to the nutrients applied with the organic matter, and to what extent they are due to increased buffer capacity (available water, CEC, pH-buffering).

Singling out the required benefit(s) of SOM and clearly distinguishing effects of increased buffer capacity from those of increased release of nutrients is crucial because these benefits/functions are very much dependent on soil type [10]. Furthermore, the desired effects will determine the type of organic residues to be produced. Finally an improved understanding of the underlying principles will allow assessing whether it is cheaper to opt for the organic matter as compared to an alternative source of nutrients.

In this paper we address the question of how increased soil organic carbon (SOC) levels, through increased buffering for water, cations and against pH-changes, translate into maize yields and increased efficiency of use of inorganic fertilizers. First we investigate how much organic matter needs to be applied to the soil to achieve a certain SOC increase for West-African conditions. This will give a more realistic view of the magnitude of the achievable SOC increase, and facilitate the discussion on potential benefits of the SOC increase in the second part of the paper. This study is mainly limited to the savanna zone in West Africa, and considers the situation where the land is cultivated continuously or almost continuously.

2. USE OF SOM MODELS TO PREDICT SOC BUILDUP

We tested RothC model version 26.3 [11] against a number of long-term experiments conducted in West Africa. Essentially, this model translates information on quality and quantity of plant litter entering the soil into changes of SOC content (expressed in Mg C ha^{-1}), thereby accounting for the effects of temperature, soil moisture, clay content (or CEC), and litter quality on the rate of decomposition. We selected data sets from replicated experiments that had a paired set of treatments: one that received high annual application rates of plant residues or manure, and one that was managed in the same way, except that it did not receive the organic matter. The difference between the reported SOC levels in the top 15 cm of the soil at the end of the trial indicated the SOC buildup resulting from the organic matter applied annually. Figure 1 shows a comparison of the model-predicted with the observed buildup. The simulated and predicted SOC buildup was normalized as follows:

$$Normalized\, buildup = \frac{SOC\ buildup\ (Mg\ C\ ha^{-1})}{annual\ application\, rate\,(Mg\, C\ ha^{-1})}$$

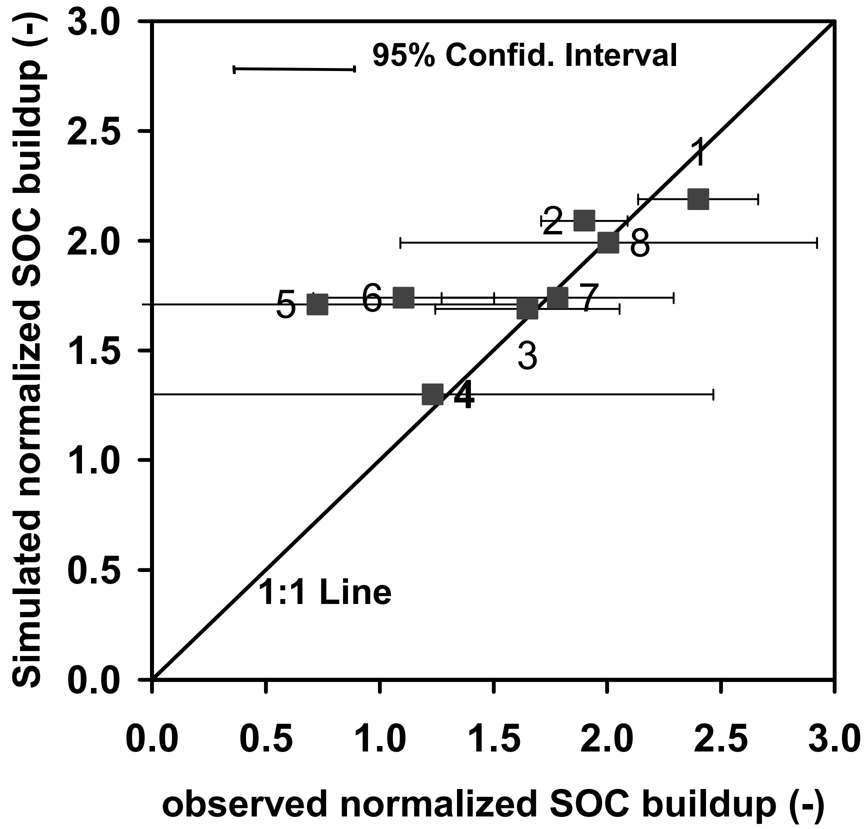

FIG. 1. Simulated against measured normalized SOC buildup from long-term experiments in West Africa. The observed normalized SOC buildup was calculated (SOC_{OM} – $SOC_{control}$) / (annual OM application rate in Mg C ha^{-1}), where SOC_{OM} is the SOC content (Mg C ha^{-1}) in the treatment that received annual applications of OM, and SOC_{CON} is the SOC content in the control treatment that did not receive OM. The numbers refer to the information on the experiments listed in Table I.

After removing the effect of application rate by normalizing, the duration of the experiment became the most influential factor: the 10-year experiments (3, 5, 6 and 7 in Fig. 1) gave a normalized buildup of about 1.75, while after 20 years (1, 2 and 8) a buildup of around 2.1 was observed. This means that per Mg organic matter – containing 0.5 Mg C – applied per ha per year, one can expect a SOC increase of 0.9 (=1.75*0.5) Mg C ha^{-1} after 10 years, and 1.05 (=2.1*0.5) Mg C ha^{-1} after 20 years.

The RothC model gave a good prediction of the SOC buildup in six out of eight data sets: only two of the eight data points significantly deviated from the 1:1 line (Fig. 1). For data point No. 5, the wide confidence interval indicated that the deviation could be due to field variation as well. Data point 6 came from the same alley-cropping experiment as point 7 (Table I). The total biomass values in the *Leucaena leucocephala* and the *Senna siamea* agroforestry systems were about equal, and the model translated this into an equal buildup. That the observed SOC buildup in the *Leucaena* system (No. 6) was much less than in the *Senna* system (No. 7) could be due to the higher litter quality of *Leucaena*. The effect of litter quality is taken into account in the model, but rather crudely. Depending on vegetation type (woodland, unimproved grassland, improved grassland, and agricultural crops), the fractions of decomposable plant material (DPM) and resistant plant material (RPM) in the incoming organic materials are set, which controls the short-term decomposition rate. Manure, being a partly decomposed organic material, is assumed to already contain some humus. The data in Fig. 1 did not allow testing whether the model properly accounts for litter quality because of the confounding between litter quality and length of growing period (optimal moisture conditions for decomposition): Only data for more resistant organic inputs (manure and groundnut shells) were available for the drier region (Samaru), while these materials were absent in the wetter sites.

Table I. Locations, coordinates, types and application rates of OM, trial duration and literature references for data shown in Fig. 1

Location[a]	Type of OM	OM rate ($Mg\ DM\ ha^{-1}\ yr^{-1}$)	Duration (years)	Reference
1. Samaru	Manure	9.4	20	[12]
2. Samaru	Manure	3.8	18	[12]
3. Samaru	Groundnut shells	5.0	9	[12]
4. Ibadan	Maize stover	12	5	[13]
5. Ibadan	Maize stover	5.5	10	[14]
6. Ibadan	*Leucaena*[b]	7.1	12	(Diels et al., unpub.)
7. Ibadan	*Senna*[b]	5.5	12	(Diels et al., unpub.)
8. Kumasi	Grass mulch	5.0	19	[8]

[a]11.2°N 7.6°E for Samaru; 7.5°N, 3.9°E for Ibadan; 6.7°N, 2.4°W for Kumasi. [b]Prunings from alley-cropping systems with *Leucaena leucocephala* Lam. (de Witt), and *Senna siamea* (Lam.) H. Irwin & Barneby hedgerow trees, respectively.

Table II. Quantity of crop and weed residues returned to the 15-cm top soil for five cropping systems in southern Benin, as derived from on-farm experiments on Terre de Barre soils (*Mucuna pruriens* and *Senna siamea* biomass data are taken from Houngnandan et al. [15] and Leihner et al. [16], respectively. Biomass production data for maize, cotton, weeds, cowpea and *Cajanus cajan* are based on unpublished data from the authors.)

System[a]	Maize stover + roots	Cotton, *Mucuna* or cowpea haulms + roots	Prunings (*Cajanus* or *Senna*)	Weeds	Total
	($Mg\ DM\ ha^{-1}\ yr^{-1}$)				
Maize/cotton relay cropping	2.4	0.2[b]	0.0	5.4	5.4.0
Maize-cowpea rotation	0.2[c]	2.1	0.0	4.3	6.6
Maize/*Cajanus cajan* relay crop	2.4	0.0	5.5	4.1	12.0
Maize/*Mucuna pruriens* relay cropping	2.4	7.3	0.0	2.8	12.5
Maize/cotton relay with *Senna siamea* mulch[d]	2.4	0.2[b]	3.8	5.4	9.2

[a]Two crops were grown in a year, either in rotation or as a relay system; the same two crops were continuously grown every year. [b]Farmers burn remaining weeds and cotton residues before planting maize. [c]Farmers burn maize and weed residues before planting the second-season cowpea crop. Burning is not practiced in the relay cropping systems. [d]*Senna siamea* trees planted as 1,600-m hedgerows per ha and pruned twice per year.

3. SCENARIO ANALYSIS ON SOC BUILDUP

Figure 2 depicts the predicted SOC buildup for different cropping systems in southern Benin as calculated with the RothC model. In all scenarios, it was assumed that maize receives mineral fertilizer at 90 kg N ha^{-1}, 30 kg P ha^{-1}, and 30 kg K ha^{-1}. No other crops were assumed to receive fertilizer, except cotton, which was assumed to receive the recommended rate of compound fertilizer.

Continuous cropping with a maize/cotton relay system, common in the region, was taken as a baseline scenario, in which crop and weed residues returned to the soil amount to 8.0 Mg DM ha^{-1} year^{-1} (Table II). A few alternative intensive systems (maize/*Cajanus* and maize/*Mucuna* relays; maize/cotton with *Senna siamea* hedgerows) could return up to 12 Mg DM ha^{-1} year^{-1} and their equilibrium SOM level will therefore be 50% higher (Fig. 2). After 20 years, the increase in SOC level realized with these "high biomass production" systems is in the order of 7 Mg C ha^{-1} or an increase of 0.33% C only in the top 15 cm of the soil. Achievable biomass production figures are likely higher in the humid forest zone (longer growing season), but definitely lower in dryer regions. Furthermore, the simulations show that the increase in SOM is slow (Fig. 2). The increase in CEC and available water, known to increase roughly proportionally to SOC content, will therefore be small during the first 2 to 5 years.

4. BENEFITS FROM SOC BUILDUP: EVIDENCE FROM LONG-TERM TRIALS

One way to look at possible interactions between organic sources of plant nutrients and mineral fertilizer, is by considering the effect of the OM additions on the yield-response curve to mineral fertilizer. Figure 3 shows two theoretical examples of this. On the horizontal axis we have depicted the available N. It is the sum of the N supplied by the soil (SOM and litter) and the fertilizer, expressed in fertilizer equivalents. The fertilizer equivalent of the quantity of nutrient supplied by the soil has been defined as the "A"-value [17]. In Fig. 3 we consider the response in total aboveground biomass to 90 kg ha^{-1} of fertilizer-N. The slope of the line connecting the data symbol for the 0-N rate with the one for the 90-N rate is the fertilizer use efficiency. Two possible effects of organic matter additions on the fertilizer response curves are considered in Fig. 3. On the upper graph, we consider the case that the effect of the repeated application of OM derives only from its N-supply, i.e., the increased "A"-value. In the event of diminishing returns to N (non-linear response curve), this always leads to lower N use efficiency (negative interaction), as is indicated by comparing the slopes of the black and gray straight lines. The OM amendments may also reduce limitations other than N, and then the N-response curve is shifted upwards on the graph, as shown on the lower graph in Fig. 3. In the example shown, the shift is large enough to offset the negative effect of the increased "A"-value, and thus give an overall positive interaction (higher fertilizer N use efficiency). In practice, the overall effect can thus be negative or positive depending on how the two effects compare.

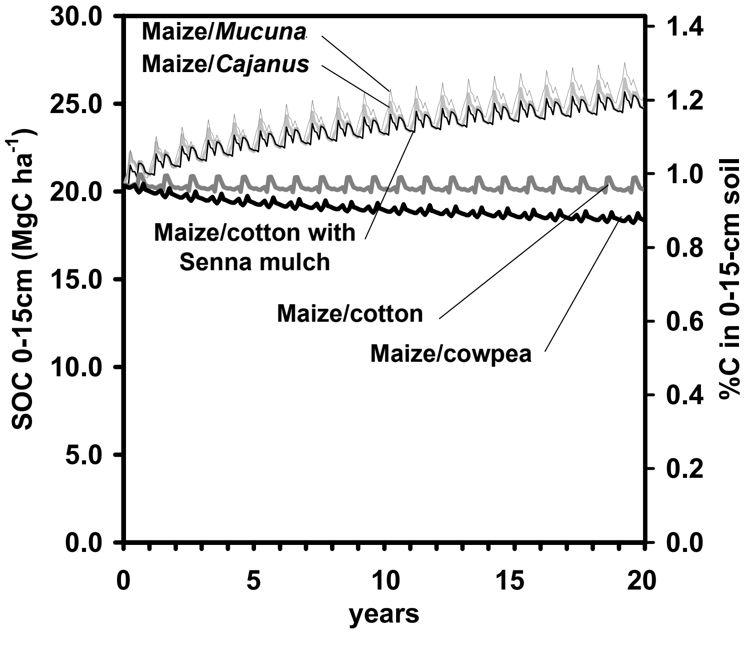

FIG. 2. SOM buildup calculated with the RothC model [11] for different cropping systems in southern Benin Republic (on Nitisols locally known as Terre de Barre). For the conversion of Mg C ha^{-1} into %C, a bulk density of 1.4 g cm^{-3} was assumed. Information on the first systems and the quantities of organic inputs to the soil is given in Table II.

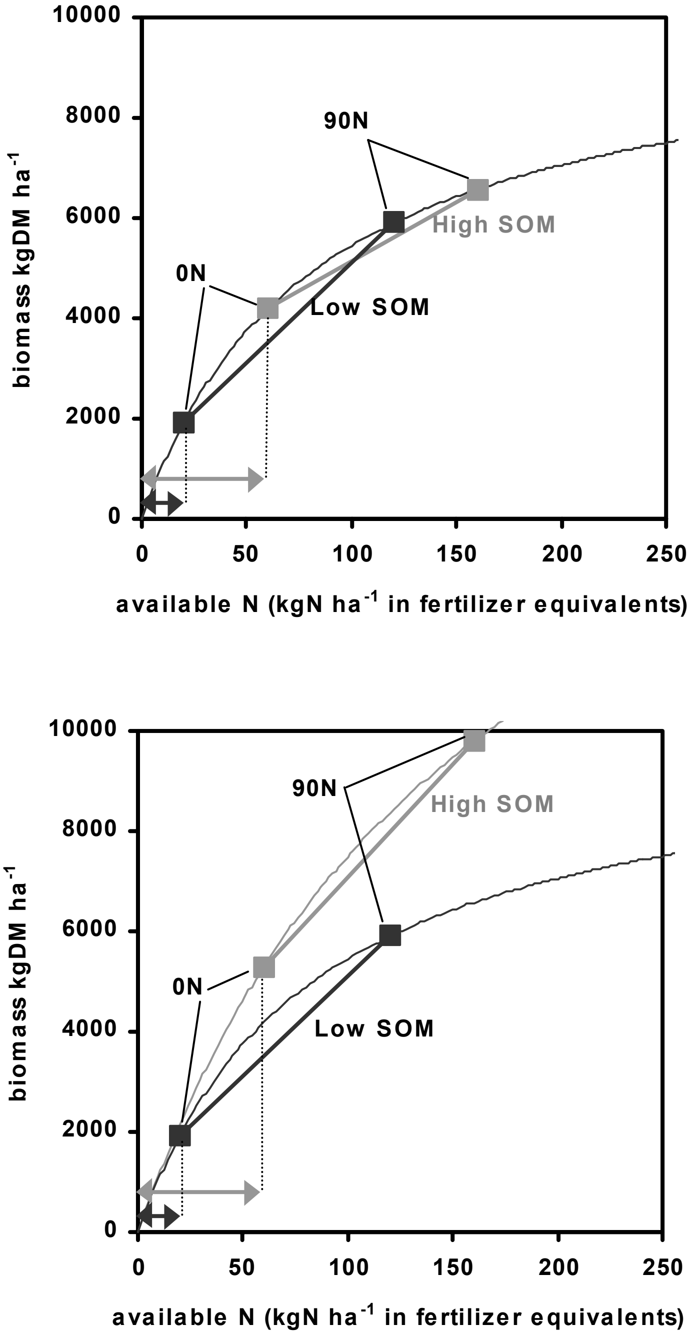

FIG. 3. Effects of organic matter additions on the response to fertilizer-N. Two hypothetical cases are considered in the theoretical example: (upper) the only effect of the OM additions is to increase the N-supply capacity of the soil (increase the "A"-value), and (lower) the OM additions increase the A-value but also reduce another limitation. The "A"-values are indicated with double-headed arrows at the bottom left corner of the graphs. To distinguish SOM levels, we used a black response curve for the "low-SOM" case and a gray curve for the "high-SOM" case. NB: the two response curves coincide in the upper graph.

An application of the concepts is provided by data (B. Vanlauwe, unpublished data) collected from a 14-year old experiment in which two alley-cropping systems were compared with a no-tree control system under continuous cropping. The N-uptake by maize was measured when either no N-fertilizer or 90 kg N ha^{-1} as urea was (split) applied. Tree-canopy removal and tree-root pruning during maize growth effectively excluded any direct influence from the trees. By using ^{15}N-labeled urea, it was possible to establish that in the no-tree control system and the agroforestry system with the non-N_2-fixing *Senna siamea* trees, the “A”-value was not different (Table III). The “A”-value was, however, significantly larger in the plots with N_2-fixing *Leucaena* hedgerows. Using these “A”-values allowed plotting the N-uptake by the maize as a function of the available N (=“A”-value + fertilizer-N) (Fig. 4). The graph indicates that the data points largely fall on the same linear response curve, which suggests that the past treatments did not reduce any limitation other than N. The larger N-uptake by maize in the *Leucaena* plots was due to an increased supply of N from the SOM under the N_2-fixing trees. This situation would have led to a negative interaction between the organic matter added in the past and the fertilizer-N if we had been operating in the part of the response curve showing diminishing returns. But in the linear part of the curve, it implies that there is no interaction.

Table III. Soil properties (0–20 cm) and “A”-value as calculated from the %N derived from fertilizer in microplot experiments with ^{15}N-labeled urea laid out in plots of a 14-year old agroforestry trial (B. Vanlauwe, unpublished data)

Treatment	%C	%N	%Ndff[a]	“A”-value[b] (kg N/ha)
No-tree + 90N	0.45	0.045	41	130
Senna + 90N	0.51	0.047	41	130
Leucaena + 90N	0.51	0.052	29	220

[a]%N derived from fertilizer.
[b](100/%Ndff – 1) × 90 kg N ha^{-1} [17].

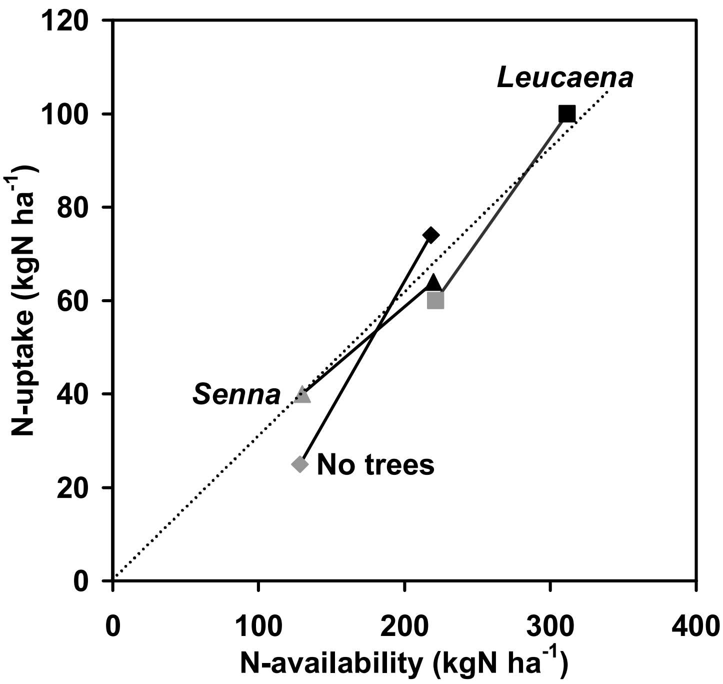

*FIG. 4. Nitrogen-response curve of maize to 90 kg urea-N ha^{-1} as observed in plots with different buildup in soil C and N due to the presence or absence of hedgerow trees (*Leucaena leucocephala *or* Senna siamea*) (B. Vanlauwe, unpublished data). The 0-N data are indicated as gray symbols, 90N data as black.*

In the data in Fig. 4 there was no indication that the repeated organic matter amendments diminished any constraint other than N. In other situations, the repeated application of plant residues might reduce another limitation, be it by supplying another limiting nutrient or by reducing losses of yield-limiting nutrients or water through improved buffering. Another possibility is that the organic-matter addition results in better root development of the crop, as was observed in a field experiment by Cisse and Vachaud [18].

Theoretically it is possible, using the above response-curve approach, to elucidate possible interaction mechanisms by separating effects due to the supply of nutrients in the organic matter from other effects (buffer capacity, increased rooting, etc.). One could observe response curves in sets of plots that received contrasting OM additions in a long-term trial, or as an alternative, compare farmers' fields that received contrasting amounts of organic matter (e.g. compound fields vs. distant fields). The response approach would, in this case, involve studying the response to every nutrient to which a response cannot be excluded. If isotopic labeling of the fertilizer is not feasible, one would have to measure the yield and nutrient uptake for at least three nutrient levels in order to be able to estimate the "A"-value by extrapolation, as suggested by Kho [19]. This approach has the advantage that possible benefits from the organic matter are expressed in fertilizer equivalents, hence the monetary value of the benefit can be quantified.

5. BUFFER CAPACITY

Instead of the somewhat elaborate response-curve technique, we can use a more mechanistic approach to investigate the extent to which increased buffering improves yields and fertilizer efficiency, and consider what is presently known about effects of increased water-retention capacity, CEC or pH buffer capacity.

The water-retention capacity is potentially important, and abundant experimental evidence is available on interactions between water stress and fertilizer use efficiency. These interactions are described by crop-growth models such as those in the DSSAT software [20]. Furthermore, the effect of the soil C content on available water capacity is well known, and is represented in many pedotransfer functions for water-retention properties. These equations, however, show that soil texture is the overruling factor and that %C has a minor effect when texture is kept constant. This is the more so because effects of increased OM inputs on SOC contents are mostly limited to the top 15 or 20 cm of soil, whereas it is the available water in the entire root zone that is of relevance. As an example, we used the pedotransfer function developed by Ritchie and Crum [21], the function that is built into the DSSAT software, to calculate the increase in plant-extractable water in the top 15 cm of soil of a sandy loam texture. The calculations indicate that, if we could increase the C content from 0.8 to 1.3%—an ambitious target, as shown earlier—we could store an extra 1-mm of water in the top 15 cm of the profile. This is almost negligible given that the total available water (the water stored between field capacity and permanent wilting point) in the root zone of a 4-week-old maize crop is at least 50 to 70 mm, depending on the soil depth. Based on data from Senegal, de Ridder and van Keulen [22] came to a similar conclusion. This argument does not, of course, exclude benefits in the seedling stage when 1 mm can make a difference. It does not exclude benefits from mulching with residues, which can effectively reduce water losses, but has little to do with SOC contents as such. Farmers' observations that mulching of crop/weed residues (vs. burning) and cover crops reduce drought effects on a subsequent crop, especially during early crop development (J. Vlaar, personal communication), could well be due to this mulching effect.

The contribution of SOM to the CEC is well known, but little is known on what minimum level of CEC is required. Without a clear threshold level, we may still identify those soils where SOC buildup could significantly increase the CEC, i.e., significantly relative to the CEC already contributed by the mineral fraction. The scenario analysis indicated that some "large biomass" systems could increase topsoil C content by 0.33% C (Fig. 2). If we assume the CEC increases by 0.4 $cmol_c\ kg^{-1}$ soil per 0.1 unit increase in %C (based on [22,23]), this would increase the CEC by 1.3 $cmol_c\ kg^{-1}$. It suggests that the effort it takes to build up SOC to increase the CEC might only make sense in soils where the CEC of the mineral fraction is below, say, 2 $cmol_c$ kg^{-1} in the topsoil. This means that possible benefits might be largely limited to Arenosols and the coarse-textured phases of the Ferralsols, which together cover about 12% of West Africa and Cameroon south of the 15°N latitude (information derived from [24]). A fraction of the Lixisols and Acrisols (those with very sandy topsoil) may also fall below the 2-$cmol_c$ kg^{-1} limit. Most Arenosols are situated in the semi-arid and arid zones where the possibility for producing the biomass for SOM maintenance is limited. Ferralsols are only marginally present in the West-African savanna, but are important in the humid forest zone (e.g. southern Cameroon). It should be kept in mind that the CEC of SOM and variable charge minerals drastically decreases with a pH decrease, implying that SOM buildup in acid soils (Ferralsols, Acrisols) has to go hand in hand with measures to keep the soil pH at the highest practical level.

Closely linked to the CEC is the pH-buffering capacity. Unlike the CEC, which results from both permanent and variable negative charges, the buffer capacity is largely determined by protonation of hydroxyl groups on sesquioxides and 1:1 clays and of functional groups of SOM, i.e. those groups that make up the variable charge [25]. An increased buffer capacity slows down acidification from NH_4-fertilizers, which might be better prevented by using a less acidifying N-fertilizer and/or combining it with lime or rock phosphate than by seeking increased buffer capacity through SOM buildup. Yet, the buffer capacity is also important for reducing NH_3 volatilization losses from urea. Nitrogen-15 experiments in Nigeria have indicated volatilization losses in the order of 10 to 40% [26,27]. Urea application raises the soil pH, thus providing ideal conditions for ammonia volatilization. The process has been described in a laboratory-tested mechanistic model by Rachhpal-Singh and Nye [28], who proved that the process is very sensitive to the pH-buffer capacity, the magnitude of which determines the extent of the pH rise [29]. So, non-acid soils with sandy top soils, and hence a low pH-buffering capacity, offer the prospect of substantial volatilization losses, and point-placement might well increase this risk by concentrating the urea [30]. As a consequence, increasing the buffer capacity by building up SOM in the surface layer of poorly buffered soils might reduce volatilization losses from urea, and this link might cause significant positive interactions between urea-N and organic amendments in the long term. There is a clear need to investigate the magnitude of the losses in relation to pH-buffer capacity in order to define minimal pH-buffer capacities. It would allow establishing critical SOM contents by considering costs of SOM buildup and savings in terms of urea, which can be weighed against cost/benefits of using alternative N-fertilizers or an improved application method.

6. CONCLUSIONS AND IMPLICATIONS

Intensive cropping systems that return larger amounts of plant biomass to the soil than current systems do exist in the West African savanna, and we know quite well how this increased OM input translates into increased SOC levels. However, the question of what SOC level we need in order to maintain sufficient CEC or pH buffering is not yet answered. As such, we cannot judge whether the effort it would take farmers to maintain SOC levels under intensive cropping in tropical conditions would be justified. If the answer to the last question is negative, the role of organic matter technologies in combination with mineral fertilizer would largely boil down to adding (biological N_2 fixation) and saving nutrients, and to benefits from mulching and crop rotation. These benefits can be weighed against the costs for farmers, and the cost/benefits of the combined organic-input/mineral-fertilizer technology can be evaluated against a purely mineral-fertilizer strategy. The possibility exists that an increased buffer capacity is important in some soils and that it is instrumental in arriving at higher efficiencies of mineral fertilizers. However, it is, to date, neither sufficiently proven nor quantified. To do so, the various benefits or functions of SOM in terms of yield need to be separated, and we have given some options to do this experimentally. The response-curve approach can indicate where the main benefits reside. There is also scope for looking in a more mechanistic way at the benefits from increased CEC or pH-buffering capacity in those soils where the mineral fraction in the top soil provides little CEC or pH buffering.

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MANAGEMENT OF ORGANIC MATTER TO ENHANCE PRODUCTIVITY OF MAJOR UPLAND CROPS OF SOUTH VIET NAM

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Abstract

Long-term cultivation reduces the fertility of arable soils by affecting the organic carbon and nitrogen (N) contents, leading to deterioration in soil structure. Maintenance of adequate levels of organic matter is an essential component of soil-fertility management in the uplands of South Viet Nam. The ^{15}N-labelling technique was used to assess whether an adapted residue-management system will supply extra N from crop residues and enhance the potential to retain added nutrients within the crop-soil system, with concomitant increases in yields. Results obtained after two cropping years of a maize-mung bean system led to these conclusions: i) fertilizer supplied 47 to 60% of the N requirement for the maize crop; ii) fertilizer use efficiency of N was 36 to 40% on a Haplic Acrisol and 41 to 46% on a Haplic Nitisol; iii) surface-applied maize stubble supplied 8.6 to 9.5% of the N requirement of the following bean crop; iv) at harvest of the first crop, 27 to 32% of fertilizer N remained in the soil and decreased to 9.6 to 12% after four consecutive crops; v) residue N fertilizer in soil supplied 6.6 to 7.7% of the N requirement of the subsequent bean crop and 1% of the third crop (maize) in the second year; vi) it is difficult to trace the fate of ^{15}N-labelled materials after a 2-year period; vii) there were no significant changes in soil properties due to surface-application of maize residues.

1. INTRODUCTION

In South Viet Nam, Acrisols, Alisols and some Lixisols under forests have been converted for agricultural use over the past 15 years. These soils occupy large upland areas. Maize and other annual crops such as soybean, mung bean, cotton and tobacco are grown with very few or no inputs in the early years after deforestation. In other areas where these crops are fertilized, much of the added fertilizer becomes unavailable due to volatilization or denitrification, leaching of nitrate, and fixation of phosphorus. The efficiency use of these fertilizers is, therefore, very low.

Long-term cultivation reduces the fertility of cultivated soils; losses of organic carbon (C) and nitrogen (N) content lead to deterioration in soil structure. Maintenance of adequate levels of soil organic matter is an essential component of soil-fertility management in the uplands of South Viet Nam. It also helps to stabilize soil structure and prevent erosion.

At harvest, stover is usually removed from the field to facilitate weeding and land preparation, to provide energy for cooking, etc. Huge quantities of nutrients are thus removed from the system. Although fertilizers are applied, due to the introduction of hybrid maize varieties, nutrient loss is a severe problem. Such nutrient mining precludes sustainability of these cropping systems. It is not known to what degree applications of crop residues to the soil surface as mulch will increase fertilizer-use efficiency and reduce nutrient losses from the cropping system. If the organic amendments lead to greater nutrient retention and uptake, the cropping system will become more sustainable.

Fertilizer N applied to soils is partially used by crops and the remaining portion may be immobilized in organic pools, fixed within clay layers or clay-humic colloids, or lost during the growing season. Residual NO_3^- in soil at harvest of maize generally increases with N rate, particularly when the optimum rate of application is exceeded.

Using ^{15}N, the main objective of the experiment was to assess whether an adapted residue-management system will supply extra N and enhance the potential to retain applied nutrients within the crop-soil system, with concomitant increases in yields of a maize-mung bean and maize-soybean systems.

2. MATERIALS AND METHODS

Since the percentages of ^{15}N atom excess in the first and the second crops were low, it seemed that the fate of ^{15}N would not be traceable for 5 years; therefore, a second batch of ^{15}N fertilizer was requested. It arrived in early 1999 and was used to set up a study of a maize-soybean rotation.

2.1. Site and location

The first experiment, a maize-mung rotation was located at Hac Dich village in Ba Ria Vung Tau province. The area had been under cultivation for 10 years. The first maize crop was planted in May 1997, followed by mung bean. In 1998, the third crop (maize) and the fourth crop (mung bean) were planted on the same field to trace the fate of ^{15}N-labelled fertilizer in soil and residues. Crop growth, yield, and soil analysis data are reported.

For the second experiment, a maize-soybean rotation was located at Hung Loc village, in Dong Nai province. The first crop was sown in May 1999 and harvested in the end of August. Soybean was sown at the same time with residue application. The crop was harvested in November 1999. In 2000, the same maize-soybean rotation was cultivated on the same plots.

2.2. Soil characteristics

The field at Hac Dich has a slope of 2 to 5%. The obvious feature is that the soil contains Fe-Mn concretions. The soil is not well developed due to poor drainage during the rainy season. According to the FAO-UNESCO classification system, the soil is a Haplic Acrisol, with skeletic and skeletic-inundic phases. The soil is shallow. The soil at Hung Loc is a Haplic Nitisol.

2.3. Crops

The first crop was hybrid maize (var. DK 888). Mung bean (local var. Mo) was sown immediately after harvesting the maize, to utilize residual moisture. At the second site, mung was replaced with soybean.

2.4.Experimental design

The experiments comprised four treatments, laid out in a randomized complete block design with four replications.

2.5. Treatments

Basal doses of major nutrient elements were set for all the treatments. Maize received 120 N-60 P_2O_5-90 K_2O (kg/ha) and mung received 40-40-60 kg/ha per element.

The main functions of the microplots were as follows. T1, to determine the flow and fate of ^{15}N-labelled fertilizer when residues were added; T2, to determine the flow and fate of ^{15}N-labelled residue; T3, to generate unlabelled residues; and T4, to determine the flow and fate of ^{15}N-labelled fertilizer when no residues were added.

2.6. Statistical analysis

The data were analysed using the SAS programme.

2.7. Other methods

Other aspects such as ^{15}N application, plant density, and soil and plant sampling were as described in the report of the second research coordination meeting.

3. RESULTS AND DISCUSSION

3.1. Climate conditions

For upland farmers, planting is determined by the start of the rains. Usually, seeds are sown after a few showers, when the soil is moist, but not too wet. The first application of N is made 7 to 10 days after seedling emergence. The second application is made two weeks later. Maize was harvested in August and the second crop was sown immediately afterwards to make use of moisture residual in the soil.

The climatic features that most affect upland cultivation are the amount of rainfall and the length of the rainy season. Total rainfall was 1,643 mm in 1998, more than that for 1997 (1,586mm). In 1997, the rainy season started unusually early, in April. Perhaps due to El Niño, heavy rains occurred in May, and washed out much of the added fertilizer and damaged the crop. There were heavy rains also at the end of August and the season continued until October, severely affecting the mung bean, explaining, at least partially, the low recovery of fertilizer N by the second crop.

3.2. Soil data

The experimental soils are acidic. The pH of the 0- to 15-cm horizon varied from 4.1 to 5.0 and increased with depth. Organic C in the surface layer ranged from 0.6 to 1%, reaching 1.5% in some plots. Nitrogen content was low, possibly due to climate conditions and the low organic matter content. Available P values were determined in soil extracts with dilute acid fluoride (Bray 2 method). Exchangeable K values were determined in the soil extracts with NH_4OAc (1 *M*) (1:10). Phosphorus and potassium were present at relative high levels as a result of fertilization.

The soil had a moderately low cation exchange capacity. The CEC of the lower horizons was slightly higher than at the surface soil. Total base cations (Ca, Mg, Na and K) were low resulting in a low percentage of base saturation. This may be due to the high Fe and Al content since the soil contains high amounts of concretions.

3.3. Nutrient content and nutrient uptake by crops

Maize grain and residues were analysed for N, P and K. Nitrogen content of the residues ranged from 0.7 to 0.9%; occasionally some samples had lower or higher concentrations. Phosphorus content of residues was similar in all samples (0.3–0.4%), whereas K was highly variable. The N, P and K contents of grain did not vary significantly. Maize grain contained approximately double the amount of N and 3 to 3.5-fold more P compared with residues.

Nitrogen was taken up in much larger amounts compared with P. Almost 70 kg N/ha were assimilated by the maize crop. Potassium was taken up in relative high amounts (30 kg/ha). There were no significantly differences in amounts of nutrient uptake between treatments, which implies that residue amendment did not affect the soil fertility sufficiently to improve growth of the subsequent crop.

3.4. The flow and fate of ^{15}N-labelled fertilizer in plants

The %^{15}N atom excess values declined from 5.35% in the labelled fertilizer to 2.6 to 2.8% in maize biomass for the T1 and T4 treatments to the first crop, respectively. These values decreased markedly for the following crop, i.e. to 0.05%. The recoveries of ^{15}N fertilizer were 37 to 40% in the first crop on the Acrisol and 40 to 45% on the Nitisol where the %N atom excess was higher (2.9–3.1%).

Results from the second crop of 1997 showed that ^{15}N added to the first season was taken up at a very low rate. More than 94% of N in the second crop was from the soil N and only 3 to 6% was derived from fertilizer applied to the previous crop.

After 1 year, very little of the assimilated N was derived from the added fertilizer (%Ndff <1%). The Nitisol showed higher N retention and supply than did the Acrisol.

Table I. The fate of N in total biomass of treatment T2 on a Haplic Nitisol

Crop	Year	$\%^{15}N$	%Ndff	Labelled fertilizer		Labelled residue	
				Ndff (kg ha^{-1})	Recovery (%)	%Ndfr	Ndfr (kg ha^{-1})
1	1999						
2	1999	0.15	2.8	0.81	0.68	4.8	0.13
3	2000	0.06	1.12	1.07	0.89	1.9	1.82
4	2000	0.03	0.65	0.16	0.13	1.1	0.28

In T2 plots, where labelled residue was added, around 4% of N taken up was derived from the residue. This means that the N use efficiency was extremely low, either due to low mineralization rate or to poor synchrony between nutrient release and uptake. Tracing the flow and fate of ^{15}N-labelled fertilizer, the %N derived from fertiliser (%Ndff) was about 2% in the first crop after residue addition. This index was smaller for the following crops.

3.5 The flow and fate of ^{15}N-labelled fertilizer in soil

Values for the recovery of ^{15}N-labelled fertilizer in soils are indicated in Table I and Figs 1 and 2 for the Nitisol at Hung Loc. In treatment T1, the recovery was 82% immediately after addition of ^{15}N fertilizer. At harvest of the first crop, 25% of added fertilizer N was found in the 0- to 15-cm layer, with 6.3% and 3.7% in the 15- to 30-cm and 30- to 50-cm layers, respectively. At harvest of the second crop in the same year, the recovery in the first soil layer dramatically decreased to 9%. Recoveries were lower at the end of the second year, after four crop seasons. A similar trend was observed with treatment T4 over 2 years.

In treatment T2, immediately after residue application, recovery in the 0- to 15-cm layer was high (80%), but it rapidly declined in the following crops. The reason for this phenomenon is not well understood. The total recoveries from soil and plant of the third and the fourth crops were about 11%, mainly from the soil budget.

4. CONCLUSIONS

Results obtained after two years of maize-bean cropping systems at two sites led to the following conclusions:

— In high-rainfall conditions, the contribution of N fertilizer was about 50% for the first crop and very low for the second and subsequent crops.
— Contributions of N from the residues were very low: 4 to 5% for the first crop and around 1% for subsequent crops.
— Organic residues from maize when applied to the soil surface showed no significant effects on dry matter production by subsequent crops.
— There are no differences in yields or harvest index between treatments T1 and T4.
— For a single application of residues, no significant changes were seen in soil properties after four cropping seasons (2 years).
— It would be difficult to trace the fate of ^{15}N-labelled fertilizer after the third crop (year 2).

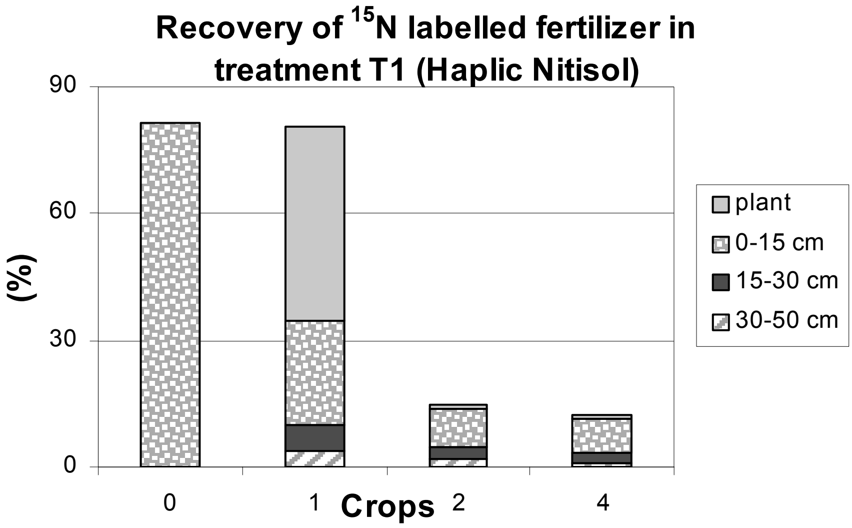

FIG. 1. Recovery (%) of ^{15}N-labelled fertilizer in the presence of unlabelled residues.

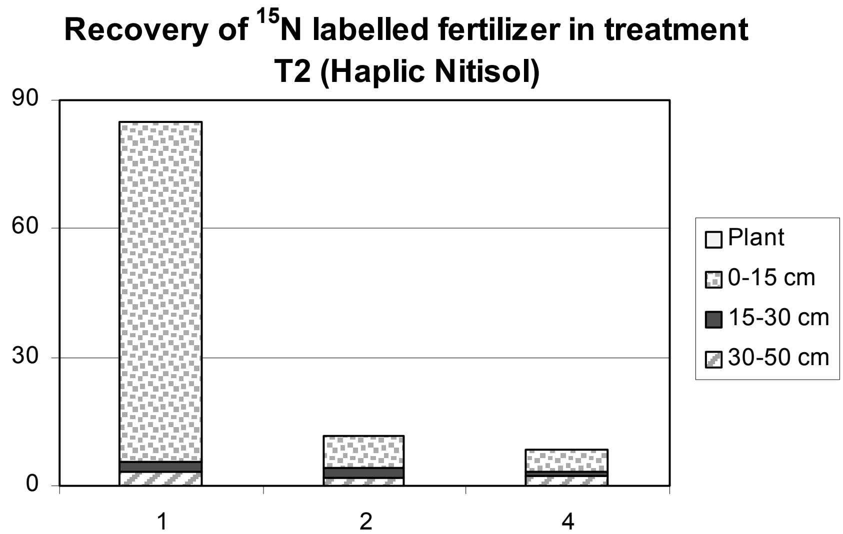

FIG. 2. Recovery (%) of ^{15}N from labelled residue.

THE INFLUENCE OF STRAW INCORPORATION AND SOIL TYPE ON THE LOSSES OF SOIL INORGANIC NITROGEN AND ITS USE BY WINTER WHEAT

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Abstract

The aim of this study was to measure the extent of immobilization caused by cereal straw incorporation in three widely differing soil types in southeast England. After harvesting the previous cereal crop, plots were treated with ^{15}N in September in two different ways. One set of plots received 50 kg N ha^{-1} as $K^{15}NO_3$ at 4.6 atom% excess, representing a pre-sowing fertilizer application. Another set received 2.5 kg N ha^{-1} as $K^{15}NO_3$ at 80.7 atom% excess. The small highly labelled application was an attempt to label the existing pool of soil nitrate. Other treatments were established with either unlabelled N or no N addition in autumn. With and without straw incorporation treatments were established on all N treatments. The ^{15}N-labelled plots were sampled in spring of the following year (April/May). Soil type, especially clay content, had a major effect on the quantity of ^{15}N retained in soil when plots were sampled about 8 months after application. Retention increased with increasing clay content. For example, for the treatment receiving 50 kg ha^{-1} of labelled N without straw incorporation, the amounts retained were 4% at Woburn (14% clay), 14% at Rothamsted (26% clay) and 33% at Northfield (39% clay). In almost all cases, incorporation of straw increased the retention of ^{15}N in soil, but the percentage increases were much smaller for the 2.5 kg ha^{-1} application than for the 50 kg ha^{-1} application. It seems likely that the small application is giving the best indication of the behaviour of soil-derived nitrate. With the 50 kg ha^{-1} application, any demand for N from increased immobilization due to straw incorporation will be met to an increased extent from the added ^{15}N-labelled inorganic N; the amount of unlabelled soil-derived inorganic N in the cultivated layer (0–23 cm) at the time of autumn ^{15}N application (between 19 and 35 kg N ha^{-1}) was of the same order as the 50 kg ha^{-1} application. The overall effect of straw on over-winter loss of labelled N was fairly small. For example, the percentage of ^{15}N unaccounted for in crop plus soil in spring at Woburn for the 2.5 kg N ha^{-1} application was 82% for "straw removed" compared to 72% for "straw incorporated." The corresponding figures for Rothamsted were 53% and 49% and for Northfield 25% and 36%, respectively. For the 50 kg ha^{-1} application, the values for "straw removed" and "straw incorporated" were Woburn 95% and 82%, Rothamsted 74% and 50%, and Northfield 49% and 29%, respectively. The results demonstrate that, in the temperate maritime climate of the United Kingdom, over-winter losses of N by leaching can be large and that pre-sowing autumn applications of N fertilizer are largely wasted. Also, there was no yield benefit from autumn-applied N. Over-winter losses of N were greatest from the low-clay sandy soil at Woburn and least from the high-clay soil at Northfield.

1. INTRODUCTION

In 1991, 36% of wheat straw was incorporated into soil in the United Kingdom, 21% was burned, and 43% was baled and removed from the field [1]. Following the ban on straw burning in 1992, the proportion incorporated has increased greatly. Despite earlier suggestions that straw incorporation would have detrimental effects on crop yields, such problems now appear to be minimal [2,3].

During the 1980s when the ban on straw burning was being considered, many UK farmers still believed that an autumn application of fertilizer N to autumn-sown cereals was essential to achieve maximum yields. Consequently there was concern that N immobilization caused by straw incorporation would decrease crop yields. By contrast, experiments with ^{15}N-labelled fertilizer applied in autumn showed very large losses due to over-winter leaching of nitrate [4] and little evidence that autumn-applied N had any benefit to yield that could not be equalled by increased N applications in spring that are used more efficiently. In fact most arable fields in the United Kingdom contain considerably more inorganic N in the soil profile in autumn than can be utilized by an autumn-sown crop during the autumn, winter and early spring period. In most circumstances it is derived from mineralization of soil organic N, though occasionally it is the result of over-fertilization.

The presence of excess nitrate in the soil profile in autumn leads to considerable leaching during winter under the climatic conditions of northwest Europe [5], with drainage water often exceeding the EU limit of 50 mg NO_3/L (11.3 mg NO_3-N/L). It seems likely that any additional immobilization of N in autumn resulting from straw incorporation might be beneficial by decreasing the amount of nitrate in soil exposed to leaching. The experiments described here, conducted on three soil types, were designed to test this possibility.

Nitrogen-15-labelled inorganic N (as KNO_3) was applied to three soil types in autumn, and straw was either incorporated or removed. Labelled N was applied in two ways: either 50 kg N ha^{-1}, representing an autumn fertilizer application, or as a very small (2.5 kg N ha^{-1}) but heavily labelled addition. The aim of the latter treatment was to label the inorganic N present in topsoil in autumn without significantly altering the quantity present.

2. MATERIALS AND METHODS

The experiments were carried out in 1984/85 at three sites in southeast England with contrasting soil types. At Woburn Experimental Farm, Bedfordshire, the soil is a free-draining sandy loam over sandy colluvium (Cambic Arenosol). At Rothamsted Experimental Station, Hertfordshire, the soil is a flinty clay loam over clay-with-flints (Chromic Luvisol). At Northfield, Oxfordshire, the soil is clay over clay drift (Eutric Vertisol). The soils contain c. 14, 26 and 39% clay, respectively, in the plough layer (Table I). In addition, at Northfield there is a perched water table that is often within 1 m of the soil surface.

At each site, on an area following cereals in 1984, the straw and stubble were burnt. Half of this area was then designated to receive chopped straw after the application of N treatments. Soil samples (0–50 cm) were taken from each half to measure inorganic N and background ^{15}N enrichment prior to N application.

In September 1984, microplots, 2×2 m, receiving either zero or c. 50 kg N ha^{-1}, were established. Those that were to continue to final grain harvest in 1985 received either no N or unlabelled KNO_3 in September 1984 and 240 kg N ha^{-1} as unlabelled NH_4NO_3 in April 1985. Other microplots were to be sampled in spring 1985 in order to study the effect of straw incorporation on soil N dynamics over the autumn-winter-early spring period. These received either c. 50 kg N ha^{-1} as $K^{15}NO_3$ at 4.6337 atom % excess or c. 2.5 kg N ha^{-1} as $K^{15}NO_3$ at 80.6784 atom % excess in September 1984.

Table I. Some physical and chemical properties of the top soil at each site

Site	FAO classific'n	Descript'n	Particle size distribution			pH in H_2O	Total N (%)
			Sand 2,000–60 μm	Silt 60–2 μm	Clay <2 μm		
			(%)				
Woburn	Cambic Arenosol	Sandy loam	64	22	14	6.6	0.102
Rothamsted	Chromic Luvisol	Flinty clay loam	16	58	26	7.7	0.159
Northfield	Eutric Vertisol	Clay	21	40	39	6.1	0.303

Table II. Treatments and times of applications and operations and Woburn (Wn), Rothamsted (Rd) and Northfield (Nd)

Site	Treatment		Labl'd N appl'd[b] (kg ha^{-1})	Date of treatment applic'n & ploughing	Date of drilling w. wheat	Date of spring sampling	Date of spring N applic'n [c]	Date of final harvest
	Straw	N appl'd[a] (kg ha^{-1})						
Wn	Burnt	0	2.56	18.IX.84	11.X.84	1.V.85	10.IV.85	28.VIII.85
	Chop[d]	0	2.56					
	Burnt	50	48.3					
	Chop	50	48.3					
Rd	Burnt	0	2.52	11.IX.84	12.X.84	8.V.85	10.IV.85	28.VIII.85
	Chop	0	2.52					
	Burnt	50	46.9					
	Chop	50	46.9					
Nd	Burnt	0	2.54	13.IX.84	26.IX.84	29.IV.85	12.IV.85	29.VIII.85
	Chop	0	2.54					
	Burnt	50	47.7					
	Chop	50	47.7					

[a]Applied as KNO_3 solution in autumn to plots continuing to final harvest. [b]Applied as $K^{15}NO_3$ solution in autumn to plots sampled in spring. [c]240 kg ha^{-1} as NH_4NO_3 solution in spring to plots continuing to final harvest. [d]Chopped straw: 9.14 t dry matter ha^{-1} incorporated.
NB: At each site, lime, basal PK fertilizers and pesticides were applied as necessary.

The labelled plots received no unlabelled N in spring prior to sampling. Being such a small amount, this latter treatment can be regarded as a zero addition to the soil nitrate pool and, assuming that it becomes well mixed, should mimic inorganic N already in the soil. The high enrichment ensures that the residues from this small addition can be measured against the background of soil N. All applications of N, whether labelled or unlabelled, were applied as a solution using a spreader designed to give even application over a known area [6]. Both rates of labelled N (2.5 and 50 kg ha^{-1}) were applied in the same volume of solution (c. 250 mL m^{-2}), equivalent to 0.25 mm of rain.

After the N application in autumn, chopped wheat straw was spread on half the microplots at a rate of 9.14 t ha^{-1} of dry matter. It was spread on 3×3 m areas, centred on the 2×2 m microplots. The N concentration in straw was 0.59% and the application contained 54 kg N ha^{-1}. There were three replicates of each of the eight treatments. Details of the actual rates and times of application are given in Table II.

Immediately after the N and straw were applied, each site was ploughed: to a depth of 23 cm at Woburn and Rothamsted, and 20 cm (followed by discing) at Northfield. A visual estimate of soil movement was made at ploughing, both forward carry on the plough body and sideways inversion of the plough slice. Seedbeds were prepared with spring-tine implements and winter wheat (cv. Avalon) was drilled, at a row spacing of 17.5 cm, 2 to 4 weeks after the treatments had been applied. In March 1985 the microplots were relocated, their positions being adjusted to allow for soil movement at ploughing. Within each microplot the central area (6 rows × 100 cm) was marked out in preparation for sampling.

2.1. Sampling

Microplots that had received labelled N in autumn were sampled in late April or early May. Whole plants from the central area were taken by digging with a hand fork. On four of the twelve labelled microplots at Rothamsted, the six rows within the central harvest area were kept separate. Rows extending to either side (east and west) of the harvest area were also sampled, as were plants from across rows to the north and south. These transect samples were analysed individually to determine whether the repositioning of the microplots had been successful. At Woburn and Northfield a limited number of rows outside the harvest area were sampled for the same purpose.

After crop sampling, soils were sampled with a Sachs Dolmar Earth Borer. Because of the expected variability of ^{15}N within plots (due to ploughing immediately after N application), four cores, each 30 cm in diameter, were taken from the top soil (0–23 cm) of each central harvest area. This large bulk of soil, c. 100 kg from each microplot, was sieved, weighed and subsampled as described by Powlson et al. [4]. Two of the four holes were then sampled to depth using a 12.5-cm diameter auger. At final grain harvest, microplots that had not received ^{15}N were cut by hand and the crop threshed on a stationary thresher to give samples of grain and straw plus chaff. Soil samples were not taken. The dates of all operations are given in Table II.

2.2. Analysis

Subsamples of crop and soil were dried and finely ground for analysis. Final-harvest crop samples were analysed for total N only by Kjeldahl digestion and Technicon Auto-Analyser. Crop and soil samples taken in spring were analysed for total N and $^{14}N/^{15}N$ ratio using an ANCA-MS linked system (Roboprep-Tracermass, PDZ Europa Ltd., Cheshire, UK). Background enrichment was measured on subsamples of soil taken prior to treatment application. A separate subsample was kept moist and extracted with 2 *M* KCl to measure inorganic N.

2.3. Statistical analysis

Data were analysed using the Genstat™ 5 statistical package [7]. The errors shown are the standard errors of the differences of the means.

2.4. Rainfall

Details of rainfall at each of the three sites are in Table III. At each site, the early autumn was wetter than average. Rainfall in September, October and November exceeded the long-term mean by about 45% at Woburn and Rothamsted, and by about 15% at Northfield.

Table III. Rainfall and difference from long-term means

		Woburn		Rothamsted		Northfield	
		(mm)					
1984	Sept	89	+37	98	+37	69	+11
	Oct	48	–7	91	+17	43	–20
	Nov	105	+43	112	+41	110	+40
	Dec	49	–5	63	–4	45	–21
1985	Jan	49	–5	58	–5	42	–19
	Feb	20	–22	29	–23	28	–17
	Mar	36	–13	38	–14	39	–5
	Apr	21	–24	31	–17	27	–17
	May	71	+21	49	–2	80	+22
	June	117	+62	102	+44	115	+66
	July	77	+26	48	–3	49	–5
	Aug	50	–17	64	+2	57	–13

Table IV. Inorganic N (ammonium + nitrate) in the soil prior to treatment application

Site	Depth (cm)	NH_4	NO_3	Total
		(kg N ha^{-1})		
Woburn	0–23	3.7	19.4	
	23–50	0.9	5.1	29.1
Rothamsted	0–23	2.3	25.6	
	23–50	1.2	9.9	39.0
Northfield (Burnt)[a]	0–23	2.4	20.3	
	23–50	1.0	3.5	27.2
(Chopped)	0–23	6.2	39.3	
	23–50	2.0	3.7	51.2

[a]Sampled before treatment application, so difference represents site variability.

3. RESULTS AND DISCUSSION

3.1. Inorganic N in soil in autumn

The amounts of inorganic N in the soil before treatments were applied are shown in Table IV. At Woburn and Rothamsted there were 29 and 39 kg N ha^{-1}, respectively, in the top 50 cm, with no trend across either site. At Northfield, however, the half of the experiment to which straw was later added contained substantially more inorganic N than the other half, 51 kg ha^{-1} compared to 27 kg ha^{-1}. The dressing of c. 50 kg N ha^{-1} of NO_3-N (either labelled or unlabelled) applied to half the treatments at each site therefore increased the pool of inorganic N by 100 to 200%. The small dressing of highly enriched ^{15}N increased the pool by only 5 to 10%.

3.2. Spring sampling

3.2.1. Transects

Data from the transect sampling across some plots at Rothamsted showed that the decision to allow for soil movement following ploughing by adjusting the position of the microplots was correct. Analysis of the wheat showed that the third row out from either side of the harvest area was considerably lower in enrichment than the central area. If the microplot had been marked out in its original position, then the harvested area would have been at a lower (incorrect) enrichment because of unlabelled soil being moved “into” the microplot.

The data also showed the degree of variability that can be expected within field microplots. The ^{15}N enrichment in the separate wheat rows ranged from 0.56 to 0.94 atom % excess. This reflects both the distribution and fate of added labelled N and that of unlabelled N coming from soil sources. Variability may have been particularly great in this experiment where the soil was cultivated immediately after ^{15}N addition.

3.2.2. Labelled N in soil

Significant quantities of the labelled N applied in autumn were retained in the soil when it was sampled in the following spring (Table V, Fig. 1). The amount was generally greatest at Northfield, which has the highest clay content: 14 to 50% of the labelled N applied was recovered in the plough layer, depending on treatment. The quantity retained was least at Woburn (2–20% of applied N), the site with the lowest clay content. The additional labelled N in deeper soil layers was generally less, except at Northfield where the amount in the 23- to 50-cm layer was, in some cases, comparable to that in the 0- to 23-cm layer (Table V, Fig. 1).

Table V. Yield, uptake of labelled and unlabelled N by wheat; recovery of labelled N in soil in spring 1985

Site / Treatment	Green crop yield	Labelled N in crop	Unlabelled N in crop	Labelled N remaining in soil			Percentage recovery of labelled N					Total recovery in crop + soil
				0–23 cm	23–50 cm	50–70 cm	In crop	0–23 cm	23–50 cm	50–70 cm	0–70 cm	
	(t dm ha^{1})	(kg ha^{-1})		(kg ha^{-1})			(%)					
Woburn												
Burnt 2.5	1.11	0.040	22.8	0.299	0.093	0.025	1.5	11.7	3.6	0.9	16.3	17.8
Chopped 2.5	1.17	0.049	24.8	0.524	0.113	0.022	1.9	20.4	4.4	0.9	25.7	27.6
SED	0.086	0.0022*	2.00	0.1235	0.0474	0.0084	0.09**	4.82	1.87	0.32	5.51	5.49
Burnt 50	1.13	0.25	22.8	1.03	0.66	0.25	0.5	2.1	1.4	0.5	4.0	4.6
Chopped 50	1.24	0.75	26.5	4.53	3.00	0.37	1.6	9.4	6.2	0.8	16.4	18.0
SED	0.099	0.112*	2.05	0.941*	1.360	0.278	0.23**	1.96*	2.80	0.59	4.90	4.92
x	1.16	na	24.2	na	na	na	1.4	10.9	3.9	0.8	15.6	17.0
SED	0.092		2.03				0.17*	0.17*	2.38	0.48	5.21	5.21
Rothamsted												
Burnt 2.5	1.58	0.148	30.5	0.872	0.084	0.096	5.9	34.5	3.3	3.8	41.7	47.5
Chopped 2.5	1.36	0.077	25.2	1.031	0.125	0.058	3.1	40.9	5.0	2.3	48.1	51.2
SED	0.088	0.0274	2.83	0.1691	0.0980	0.0142	1.11	6.70	3.90	0.57	7.54	7.41
Burnt 50	1.92	5.33	31.8	4.74	0.00	1.99	11.4	10.1	0.0	4.3	14.4	25.7
Chopped 50	1.60	4.27	27.9	13.76	4.12	1.54	9.1	29.3	8.8	3.3	41.4	50.5
SED	0.273	2.560	3.94	2.070*	0.287***	0.874	5.47	4.41*	0.61***	1.87	4.18**	6.51*
x	1.61	na	28.8	na	na	na	7.3	28.7	4.3	3.4	36.4	43.7
SED	0.203		3.43				3.95	5.67	2.79	1.38	6.09*	6.97
Northfield												
Burnt 2.5	2.15	0.313	46.4	0.910	0.600	0.092	12.3	35.8	23.6	3.6	63.0	75.3
Chopped 2.5	1.51	0.168	35.2	1.049	0.316	0.085	6.6	41.3	12.4	3.4	57.1	63.7
SED	0.115**	0.0444*	4.49	0.142	0.1458	0.0057	1.76*	5.61	5.73	0.22	10.4	11.20
Burnt 50	2.51	8.45	49.4	6.91	7.57	1.61	17.7	14.5	15.9	3.4	33.7	51.4
Chopped 50	2.09	4.93	39.8	24.12	2.60	2.52	10.3	50.5	5.5	5.2	61.2	71.5
SED	0.350	1.628	5.49	6.140*	2.300	0.530	3.40	12.87*	4.83	1.11	13.3	14.0
x	2.06	na	43.0	na	na	na	11.7	35.5	13.9	3.9	53.3	65.0
SED	0.261		4.76				2.72	9.93	6.00	0.80	12.4	13.1

FIG. 1. Percentage of labelled N remaining in soil, 0–70 cm, at anthesis.

With only one exception, the percentage retention of ^{15}N from the 2.5 kg N ha^{-1} application was greater than from 50 kg N ha^{-1} for both straw treatments (Table V, Fig. 1). This is presumably a pool-dilution effect: in a given straw treatment there will be a certain demand for N due to immobilization processes, irrespective of the quantity of inorganic N present. Where 50 kg N ha^{-1} is added, this demand will be met from the combined pool of soil-derived N and added labelled N. Where only 2.5 kg N ha^{-1} is added, the same demand will be met from a smaller pool. For a full discussion of these effects, see Refs. [8–10].

Two processes will contribute to the retention of ^{15}N in soil: (a) that part of the N taken up by roots that is not translocated to tops, and (b) immobilization through the action of the soil microbial biomass. The latter process would be expected to be greater where straw was incorporated and, in almost all cases, this was so. In the case of the 50 kg N ha^{-1} application, about three to four times more labelled N was retained in the 0- to 23-cm soil layer where straw was incorporated compared to where it was removed. In terms of quantities of labelled N, as opposed to percentage, the largest difference was at Northfield: 24.1 kg N ha^{-1} was retained in the straw-incorporated treatment compared to only 6.9 in the burnt. The corresponding values for incorporated and burnt at Woburn were 4.5 and 1 kg N ha^{-1} and, at Rothamsted, 13.8 and 4.7 kg N ha^{-1}. Although there were clear trends between the two straw treatments at all three sites, many of the differences were not statistically significant because of large variability among replicate plots. The particularly small retention at Woburn is, in part, because much of the labelled N would have been lost by leaching; 42 mm of rain fell within 2 days of application.

3.2.3. Crop growth in spring

Yields of dry matter in spring are shown in Table V. At Woburn there were no significant differences between treatments, and yields were about 1.2 t ha^{-1}. At Rothamsted and Northfield, where the crops were more advanced in development, yields were larger. At these latter sites, microplots that had received straw in the autumn yielded less than plots that had been burnt. The highest yields were on plots given 50 kg N ha^{-1} in autumn and no straw. The lowest yields were on plots receiving 2.5 kg N ha^{-1} plus straw. However, errors were large at both sites and differences were rarely significant. Some of the differences in yield between treatments can be explained in terms of tiller numbers. At each site the highest yield was on plots with the highest number of tillers per m^2 (burnt + 50 kg N ha^{-1} at Rothamsted and Northfield, chopped + 50 kg N ha^{-1} at Woburn). However, there was no consistent effect of treatment on tiller number. Perhaps surprisingly, Woburn with the lowest green crop mass had, on average, the highest number of tillers and Northfield with the highest green crop mass at this time, had the lowest number of tillers. This trend in tiller numbers was continued through to final harvest (see later section), but the trend in yield was not.

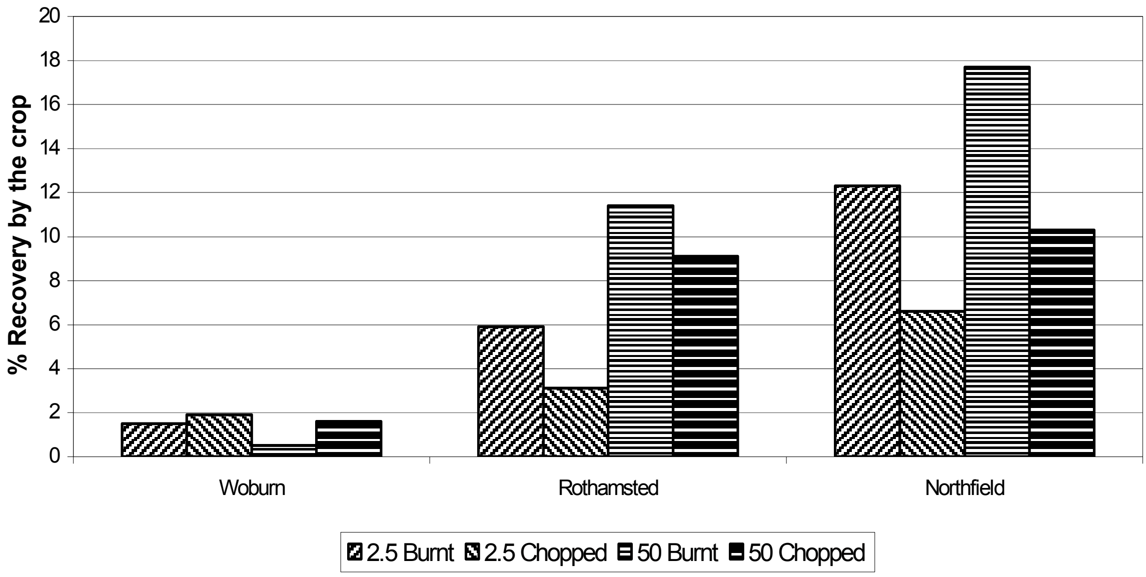

FIG. 2. Percentage of labelled N taken up by the crop by anthesis.

3.2.4. Crop N content in spring

Wheat was drilled at Woburn, Rothamsted and Northfield 23, 31 and 13 days, respectively, after the application of treatments and ploughing. If straw addition caused increased immobilization of N it would be expected that the quantity of N (both labelled and unlabelled) available for crop uptake would be decreased for at least part of the autumn/winter period. With labelled N, this trend was observed at Rothamsted and Northfield; when wheat was sampled in spring the uptake of labelled N was slightly less in the straw-incorporated treatments than in the burnt (Table V, Fig. 2). This trend was apparent for both the 2.5 and 50 kg N ha^{-1} treatments and corresponds with the greater retention of ^{15}N in soil in the straw-incorporated treatments. There were no significant differences between straw treatments in wheat total N content in spring although there was a trend towards smaller uptakes of N in the straw-incorporated treatment at Northfield and, to a lesser extent, at Rothamsted.

It is clear from Table V that the N content of all crops when sampled in spring was dominated by unlabelled N coming from soil sources; the greatest recovery of labelled N applied in autumn was 8.5 kg N ha^{-1} (18% of that applied) from the 50 kg N ha^{-1} applied to the burnt treatment at Northfield. In all other cases it was much less, although where 50 kg N ha^{-1} was applied at Rothamsted the proportion of labelled N present in the crop in spring was similar: about 14% of the total.

At Woburn, recovery of the labelled N by the crop was extremely small, less than 2% of that applied. Surprisingly, there were significant differences between the treatments and these were the reverse of those at Rothamsted and Northfield (Table V). More labelled N was recovered where straw had been incorporated, and a slightly smaller proportion of N was recovered on average, where 50 kg ha^{-1} had been applied compared to the smaller dressing.

3.2.5. Overall losses

The overall losses of labelled N from the crop-soil system are shown in Table VI. Recoveries were dominated by what was retained in the soil rather than what was taken up by the crop (see Table V). Therefore, overall losses tended to follow the same trend.

Table VI. Fraction of labelled N unaccounted for in crop and soil (0–70 cm)

Treatment	Woburn	Rothamsted	Northfield	SED
	(%)			
Burnt 2.5	82.2	52.5	24.7	
Chopped 2.5	72.4	48.8	36.3	
SED	5.49	7.41	11.2	
Burnt 50	95.4	74.3	48.6	
Chopped 50	82.0	49.5	28.5	
SED	4.92	6.51^{**}	14.0	
Burnt	88.8	63.4	36.6	
Chopped	77.2	49.2	32.4	
SED	3.69^{*}	4.93^{*}	8.94	
2.5	77.3	50.6	30.5	6.23^{***}
50	88.7	61.9	38.5	6.29^{***}
SED	3.69^{*}	4.93	8.94	
Overall mean	83.0	56.3	34.5	4.29^{***}
Overall SED	5.21	6.97	12.7	

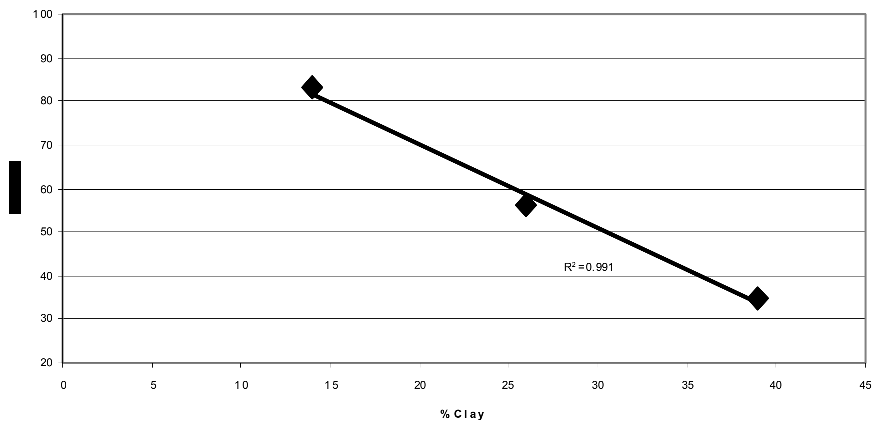

FIG. 3. Effect of percent clay content on overall loss (%) (R^2=0.991)).

The biggest losses were on the sandy soil at Woburn, with up to 95% of the labelled N being lost where 50 kg N ha^{-1} had been applied but no straw incorporated. This loss was limited to 82% when straw was added. There was a similar reduction, 82% to 72%, when straw was added with the smaller 2.5 kg N ha^{-1} dressing. At Rothamsted and Northfield, losses were reduced by 25% and 20%, respectively, when straw was applied with the higher N dressing. Where 2.5 kg ha^{-1} was applied, there was no significant effect of straw incorporation at Rothamsted whilst at Northfield the situation seemed to be reversed, i.e. a smaller loss where straw had not been incorporated. However, the errors associated with the analysis of soil from the three replicates making up this treatment were very large, showing considerable spatial variability.

Averaged over all treatments, losses on the three soil types were very significantly different, 83%, 56% and 35% at Woburn, Rothamsted and Northfield, respectively, and were closely correlated to clay content (Fig. 3).

Table VII. Loss of soil derived inorganic N

Site	Inorganic N (0–50 cm) present in autumn (kg ha^{-1})	Loss[a] of a 2.5 kg ha^{-1} labelled N dressing applied to		Minimum overwinter loss of soil-derived N	
		Burnt	Chopped	Burnt	Chopped
		(%)		(kg ha^{-1})	
Woburn	29	83	73	24	21
Rothamsted	39	56	51	22	20
Northfield (burnt)	27	28		8	
Northfield (chopped)	51		40		20

[a]i.e. unaccounted for in crop or soil (0–50 cm); from Table V.

3.2.6. Over-winter losses of soil-derived N

If it is assumed that the percentage loss of labelled N from the 2.5 kg N ha^{-1} treatment represents the percentage loss of unlabelled inorganic N present in the soil profile in autumn, total over-winter losses can be estimated. This is shown in Table VII. The values will underestimate total losses as, presumably, additional nitrate will have been mineralized after the 2.5 kg N ha^{-1} addition was made in September and an unknown proportion of this will have been lost. They will also underestimate real losses because the percentage loss of ^{15}N refers to nitrate in the plough layer. A greater proportion of nitrate deeper in the profile will be leached as it will be out of reach of the root system of newly established wheat plants in the autumn and winter periods. The calculations in Table VII refer only to the inorganic N (mainly nitrate) measured to a depth of 50 cm (Table IV).

The calculations in Table VII show that straw incorporation would be expected to have little or no effect on total N losses. In this context, losses are presumed to be predominantly from nitrate leaching. This is also suggested by the work of Ocio et al. [11].

3.2.7. Crop yield and N uptake at final harvest

After the wet autumn of 1984, conditions in spring and summer 1985 were good for cereal growth. Rainfall was below average at all three sites until May or June and it was cool from June to August, which usually helps ensure good grain filling. Yields of grain and straw are given in Table VIII.

Yields at Woburn and Rothamsted were high (9.2–9.9 t ha^{-1}), particularly so at Woburn where yield can be reduced if water is limiting. The experiments at Woburn and Rothamsted reported here were each adjacent to larger, long-term straw experiments that were in their first year. Yields on comparable plots on these two main experiments were similar to those on our sites [12]. Yields at Northfield were 2 to 3 t ha^{-1} lower than at Woburn or Rothamsted; the apparent advantage that the crop at Northfield enjoyed in spring was not reflected in final grain yields.

Many of the trends observed in spring between treatments were still apparent at harvest, although they were not necessarily statistically significant. At Woburn, plots to which chopped straw was added yielded slightly more than those without. At Northfield they yielded less. The effect of 50 kg N ha^{-1} applied in autumn was more consistent, though small. At each site, plots given this treatment yielded more grain than where no N had been applied: 3.7, 5.3 and 7.6% extra grain at Woburn, Rothamsted and Northfield, respectively, though none of the differences were statistically significant.

Table VIII. Yield and N uptake at harvest

Site	Treatment	Grain yield at 85% dm	Straw yield at 85% dm	N uptake by grain	N uptake by straw	Total N uptake
		($t\ ha^{-1}$)		($kg\ ha^{-1}$)		
Woburn	Burnt 0	9.25	7.95	182	56	238
	Chopped 0	9.51	8.54	191	60	251
	SED	0.214	0.096**	5.9	1.8	4.7
	Burnt 50	9.69	8.57	190	62	252
	Chopped 50	9.77	8.90	190	65	255
	SED	0.208	0.240	4.6	5.0	4.0
	x	9.55	8.49	188	61	249
	SED	0.211	0.183	5.3	3.8	4.3
Rothamsted	Burnt 0	9.30	7.81	179	52	231
	Chopped 0	9.35	8.12	178	54	232
	SED	0.355	0.241	3.5	1.9	2.4
	Burnt 50	9.59	7.96	183	57	240
	Chopped 50	9.87	8.34	191	55	246
	SED	0.450	0.210	7.4	2.2	8.5
	x	9.53	8.06	183	54	237
	SED	0.405	0.226	5.8	2.1	6.2
Northfield	Burnt 0	6.33	6.59	139	49	188
	Chopped 0	6.04	6.08	132	43	175
	SED	0.278	0.232	3.4	2.7	5.8
	Burnt 50	7.19	7.56	155	54	209
	Chopped 50	6.13	6.75	131	47	179
	SED	0.305*	0.416	7.9*	4.9	10.3*
	x	6.42	6.74	139	48	188
	SED	0.292	0.337	6.0	4.0	8.4

Treatment had no effect on %N in grain or straw (data not shown). The total amount of N in the crop at harvest was not affected by treatment except at Northfield where plots that had received straw took up less N, in line with the lower yields. By subtracting the amount of N in the crop in spring from the amount present at harvest, we can estimate the amount taken up by the crop between spring and harvest. (This is not strictly correct as the ^{15}N microplots were sampled 2 to 4 weeks after fertilizer N was applied to those plots that were to continue to final harvest.) As described earlier, the amount in the crops at Woburn and Rothamsted in spring was small. Between spring and harvest, the crop took up, on average, c. 225 and 205 kg N ha^{-1} at Woburn and Rothamsted, respectively, but significantly less, c. 140 kg ha^{-1} at Northfield. Much of this N would have come from the 240 kg N ha^{-1} fertilizer dressing applied in April, some from atmospheric deposition and some from mineralization of soil organic matter. Presumably the much lower uptake at Northfield was due to continued immobilization, denitrification or ammonium fixation on this heavy clay soil. There is an indication that, on some treatments at Woburn and Rothamsted, c. 5% more N was taken up during this period where straw had been applied the previous autumn; possibly as N is remobilized. However, at Northfield on plots given 50 kg N ha^{-1} plus straw the previous autumn, c. 12% less N was taken up during summer, presumably reflecting greater immobilization.

4. CONCLUSIONS

Several points emerge from the results reported here.

— Soil type had a very significant effect on the amount of N immobilized and retained in the soil profile. At Woburn, Rothamsted and Northfield where the clay content is 14, 26 and 39%, respectively, the amounts of labelled N remaining in the profile from the previous autumn were, on average, 16, 36 and 54% (SED 4.1***).

— Although the overall amounts of N immobilized at Woburn were smaller, the incorporation of straw on the lighter, sandy soil had a proportionately greater effect than on the heavy clay soil at Northfield; the effect at Rothamsted was intermediate.

— Adding straw may protect some inorganic N from loss. Although the "extra" N immobilized compared to that immobilized where straw is not incorporated is likely to be small, it may help to keep concentrations of NO_3-N in any drainage water below the 50 mg L^{-1} EC limit. However, in the longer term, it may maintain or even raise the organic matter content of the soil [13]. This, in itself, may be desirable on light- to medium-textured soils [14], but could eventually lead to greater mineralization and larger losses of N.

— When the incorporation of straw started to become more common in the mid-1980s, fears were expressed that the immobilization of soil-derived inorganic N might lead to a reduction in crop yields; this has been largely discounted by various authors [3,15,16]. In these experiments, there was no indication that yields at Woburn or Rothamsted were adversely affected by the incorporation of straw. If anything, yields were higher following the addition of straw, although this increases was not significant. However, at Northfield there is some evidence to suggest that grain yield was reduced where straw had been ploughed in; significantly so where 50 kg N ha^{-1} had also been applied.

ACKNOWLEDGMENTS

Rothamsted-Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council of the United Kingdom. I. Cracuin acknowledges financial support from a European Union Fellowship.

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STUDIES OF ORGANIC MATTER TURNOVER AND NUTRIENT BUILDUP IN A BANGLADESH SOIL FOR SUSTAINABLE AGRICULTURE

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Abstract

A field experiment was conducted with a wheat-rice cropping system over four consecutive years, 1996 to 2000. The objective was to assess whether an adapted residue-management system would enhance the potential to retain added nutrients within the crop-soil system with concomitant increases in yields. To synchronize nutrient release from organic amendments with nutrient uptake by the crop, another experiment was conducted in 1997/98. The rate of decomposition and the release of N from crop residues were determined in an incubation study conducted under field conditions in small ^{15}N microplots contained within cylinders. Results indicated that wheat residue was enriched in ^{15}N at 4.3 to 5.5% a.e., where 10.5% ^{15}N a.e. labelled ammonium sulphate had been applied. Total yields of rice (grain + straw) increased significantly in treatment T_2 where ^{15}N-labelled crop residue was applied at 5 Mg ha^{-1}, i.e. 14.0, 11.6, 12.6 and 12.6 Mg ha^{-1} in the first, second, third and fours years, respectively. The ^{15}N-labelled wheat residue contributed about 3 kg N ha^{-1} to the total N pool of the first crop of rice in treatment T_2 and 0.99, 0.39 and 0.15 N kg ha^{-1} in the second, third, and fourth years respectively. The ^{15}N fertilizer, which was applied to the first crop (wheat), was gradually recovered in the subsequent crops in plots where ^{15}N-labelled crop residues were incorporated, and more ^{15}N was retained in the soil than was taken up by plants. In the incubation study, N release from crop residues showed an irregular relationship with crop-N uptake. Changes were observed in soil mineral N following addition of crop residues. The greatest release of ^{15}N from residues was recorded with the longest incubation period.

1. INTRODUCTION

Declining soil organic matter (SOM) causes a variety of problems that includes poorer soil physical conditions, greater risk of erosion, poorer water retention, less cycling of nutrients through organic forms, and, probably, decreased biodiversity [1]. The aboveground parts of the major field crops are removed from the field with the harvest of grains. In Bangladesh, the biomass is mainly used as fodder and fuel. A huge quantity of nutrients is thus taken from the system, leading to rapid decline in SOM and decreased nutrient supply, which affects the sustainability of crop production. Maintenance of adequate levels of SOM is an essential component of soil-fertility management [2]. It also helps to stabilize soil structure and to prevent erosion.

To determine whether the application of residues increases nutrient-use efficiency by crops requires long-term investigations. If organic amendments, including crop residues, lead to greater nutrient retention and uptake, the cropping system would become more sustainable and productivity would be maintained. Locally available crop residues can be used in conjunction with inorganic fertilizers and when harmony is achieved, the efficiency of use of added nutrients and those already present can be enhanced [3]. The use of ^{15}N helps to determine how quickly and to what extent N contained in fertilizer and residues is released for crop uptake.

Thus, within the framework of the Joint FAO/IAEA Division's Co-ordinated Research Project on "The Use of Isotope Techniques in the Management of Organic Matter and Nutrient Turnover for Increased, Sustainable Agricultural Production and Environmental Preservation," studies were carried out to:

- assess whether an adapted residue-management system enhances the potential to retain added nutrients within the crop-soil system with concomitant increase in yields, and
- synchronize the release of nutrients from crop residues with uptake of nutrients by the current crop.

Table I. Physico-chemical properties of the soil

Soil depth (cm)	Particle-size distribution Sand (%)	Silt (%)	Clay (%)	Texture	pH	SOM (%)	Total N (%)	Avail. P (ppm)
0–15	49	38	13	Loam	6.1	1.2	0.08	13
15–30	59	28	13	Sandy loam	5.8	0.64	0.05	17
30–50	74	10	16	Sandy loam	5.8	0.50	0.06	12

Soil depth (cm)	Avail. K (% mEq)	EC (dS m^{-1})	CEC (mg/100g)	Bulk density (g cm^{-3})	Moisture content at FC[a] (cm^3 cm^{-3})	Maximum WHC[b] (%)
0–15	0.20	0.30	10.6	1.38	0.297	50
15–30	0.20	0.25	8.7	1.32	0.356	52
30–50	0.10	0.30	7.5	1.33	0.364	52

[a]Field capacity, i.e. –30 kPa. [b]Water-holding capacity.

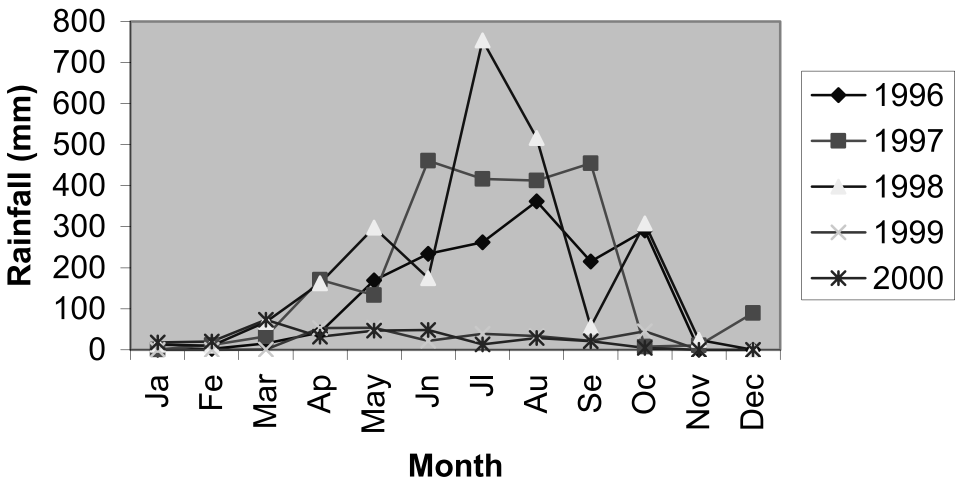
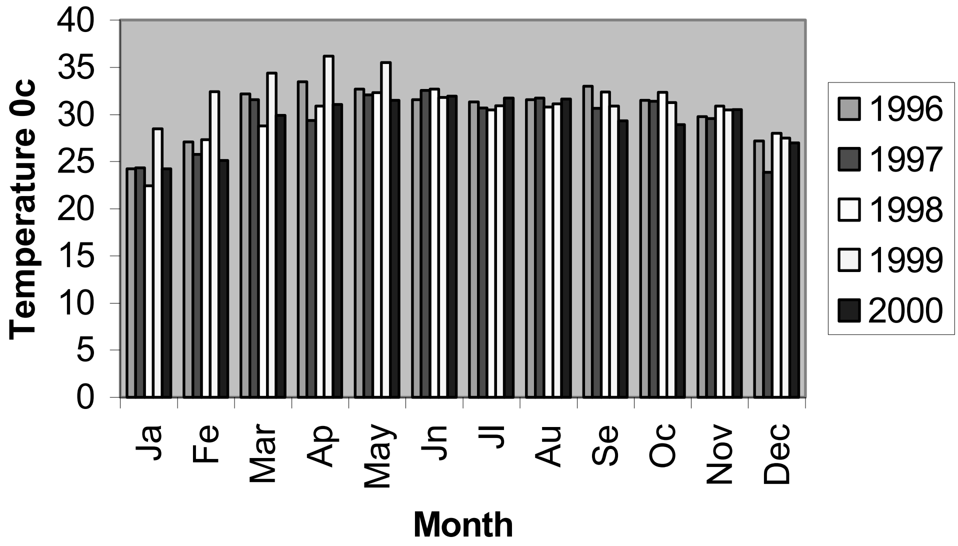


FIG. 1. Monthly rainfall, 1996–2000.

2. DESCRIPTION OF THE RESEARCH

2.1. Field experiment

A field experiment was carried out over four consecutive years, 1996 to 2000, at the experimental farm of the Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh, on a grey soil in agro-ecological zone 9, the Old Brahmaputra floodplain, a Haplaquepts according to USDA taxonomy. The experimental area is located at 26°36' N and 86°34' E. The physical and chemical properties of the soil, determined using standard laboratory methods, and rainfall and temperature data during the experimental period are presented in Table I and Figs. 1 and 2, respectively.



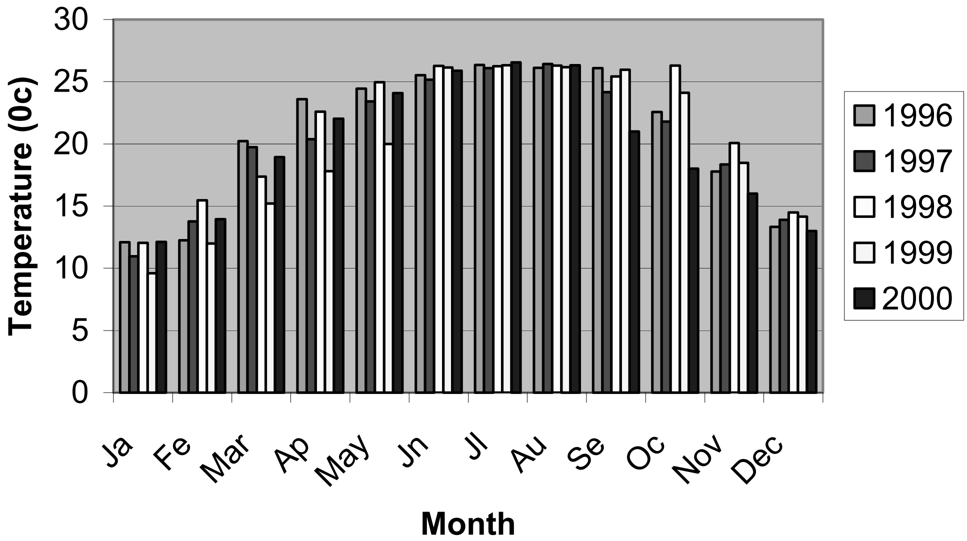


FIG. 2. Maximum (upper) and minimum (lower) monthly air temperatures, 1996–2000.

2.1.1. Year 1, growing season 1, wheat

An experiment was established in a randomized complete block design with four treatments replicated four timres. T_1—to determine the fate of ^{15}N fertilizer with residues, T_2—to determine the fate of ^{15}N-labelled residue with residues (normal ammonium sulphate was used in the second crop), T_3—to generate unlabelled residues, and T_4—to determine the fate of ^{15}N fertilizer without residues. The individual plot size was 10×6 m with an ^{15}N microplot of 4×4 m. At the initiation of the experiment, the basic soil properties were determined: soil texture, soil pH, CEC, EC, available P and K, etc. (Table I).

Nitrogen-15-labelled ammonium sulphate (10.48% a.e.) was applied in four splits to the microplots. Normal ammonium sulphate was applied to yield plots. Other fertilizers were applied in a basal dose at the time of final land preparation (kg ha^{-1}): 17.5 P, 50 K, 20 S, and 5 Zn. The ^{15}N-labelled ammonium sulphate was applied to the microplots as homogeneously as possible following experimental guidelines. Irrigation was applied at 42 days and the amount was calculated using neutron probe data. Wheat yields (grain and straw) were determined from the yield plots of all the treatments. Plant samples from ^{15}N microplots of the T_1 and T_4 treatments were taken to determine total N and ^{15}N contents and also from the yield plots of T_2 to determine total N in seed and residue.

Soil samples were taken from ^{15}N plots of T_1 and T_4 after wheat harvest, from three depths: 0–15, 15–30, and 30–50 cm. The total N pool and $\%^{15}N$ a.e. were determined at BINA's soils laboratory and also at IAEA. The ^{15}N-labelled wheat residues were stored for subsequent use in crop 2 (rice).

2.1.2. Year 1, growing season 2, rice

The experiment was established using the plots of the preceding wheat crop with the same four treatments. Unlabelled wheat residues in the microplots of treatment T_2 were removed and ^{15}N-labelled wheat residues were applied as obtained from T_1. After the application of ^{15}N-labelled wheat residues at 5 Mg ha^{-1} to the microplots of T_2, samples were taken in order to determine the ^{15}N recovery in the soil. Rice was grown as the second crop as no suitable legume was available for growing in the monsoon. At harvest, rice yields (grain and straw) were recorded. Samples were taken from ^{15}N microplots to determine total N and ^{15}N contents. Soil samples were also taken from the ^{15}N microplots of T_2 after the rice harvest. Nitrogen-15-labelled rice residues from the microplots of T_1, T_2 and T_4 were removed and stored for future use. Nitrogen-15-labelled rice residues from T_1 and T_2 were replaced with unlabelled rice residue from T_3. Soil organic matter content was determined from 0- to 15-,15- to 30-, and 30- to 50-cm depths after harvest of both wheat and rice crops in the first year.

2.1.3. Year 2, growing season 1, wheat

This part of the experiment was established in the same experimental layout, where unlabelled rice residue from the T_3 treatment (collected from the first year) was applied in T_1 and T_2 treatments at 5 Mg ha^{-1}. In T_3, wheat was grown with normal fertilizer and with no crop residue to generate unlabelled wheat residue. Nitrogen-15-labelled wheat residue was grown in the microplots of T_4 to study the fate of labelled ^{15}N fertilizer applied without residue during year 1, growing season 1. Wheat yields (grain and straw) were recorded from all of the yield plots. Plant and soil samples were taken from T_1, T_2 and T_4 microplots for determinations of total N and ^{15}N content and stored for use with the next crop.

2.1.4. Year 2, growing season 2, rice

The wheat-rice-fallow sequence was continued with application of wheat residue from T_3 to T_1 and T_2 to determine the fate of ^{15}N fertilizer with residue and ^{15}N-labelled residue with residues, respectively. Unlabelled rice residues were produced in T_3 and ^{15}N-labelled rice residues were analysed to determine the fate of ^{15}N fertilizer without residue in T_4.

2.1.5. Year 3, growing season 1, wheat

In this third year, with wheat, the experiment was continued with the application of residue from T_3 to T_1 and T_2 with the determination of the fate of ^{15}N fertilizer with residue and ^{15}N-labelled residue with residues, respectively. Unlabelled wheat residues were produced in T_3 and ^{15}N-labelled wheat residues from T_4 were analysed to determine the fate of ^{15}N fertilizer without residue in T_4.

2.1.6. Year 3, growing season 2, rice

In this part of the experiment, conducted with rice, the wheat-rice-fallow sequence was continued with application of wheat residues from T_3 to T_1 and T_2 to determine the fate of ^{15}N fertilizer with residue and ^{15}N labelled residue with residues, respectively. Unlabelled rice residues were produced in T_3 and ^{15}N-labelled rice residue were analysed to determine the fate of labelled ^{15}N fertilizer without residue in T_4 according to the experimental protocol.

2.1.7. Year 4, growing season 1, wheat

This was the last year of the experiment, conducted with wheat, with application of residue from T_3 (which was harvested from the third-year of the experiment) to T_1 and T_2 to determine the fate of ^{15}N fertilizer with residue and ^{15}N-labelled residue with residues, respectively. Unlabelled wheat residues were produced in T_3. Nitrogen-15-labelled wheat residue from T_4 was analysed to determine the fate of ^{15}N fertilizer without residue in T_4.

2.1.8. Year 4, growing season 2, rice

This final component of the experiment was conducted with rice, again in the same plots as the previous years, with application of wheat residue from T_3 (harvested from year 4, growing season 1) to T_1 and T_2 to determine the fate of ^{15}N fertilizer with residue and ^{15}N-labelled residue with residues, respectively. After completion of the 4 years of experiments, the data were collected for compilation of results and statistical analyses.

2.2. Incubation study

An incubation study was conducted in 1998–1999 to synchronize the release of nutrients from organic residues with uptake of nutrients by the crop. Wheat residues that were highly labelled with ^{15}N in the first year of the field experiment were used. The experiment was conducted under field conditions in small ^{15}N microplots contained within cylinders of diameter 20 cm and length 50 cm. The quantity of the ^{15}N-labelled residue added was similar to the quantity of residue harvested.

The residue application schedule was as follows:

— R_1, residue applied when the crop (wheat) that produced the labelled residue was harvested,
— R_2, residue applied 2 weeks before the next crop (rice) was seeded,
— R_3, residue applied at the time of sowing the crop (rice), and
— R_4, residue applied at 4 weeks after sowing and at the start of tillering.

The cylinders were placed in the experimental field, kept free of weeds and no plants were grown. Soils from the cylinders were sampled destructively five times, keeping in view the critical growth stages of wheat, i.e. at weeks 4, 6, 8, 10, and 12 after planting. Plant samples were also collected simultaneously. Soil and plant samples were analysed for total N, ^{15}N a.e., and mineral N (both NH_4 and NO_3). Total N and ^{15}N were expressed as kg ha^{-1}.

Table II. Total N and ^{15}N-derived data for wheat (year 1, growing season 1)

Treatment	Plant part (Mg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	%Ndff	Fert. N yield (kg ha^{-1})	%N recovery
T_1	Grain 2.40	1.9	43.1	4.33	41	17.8	30
	Straw 3.66	0.24	12.2	4.59	44	5.35	8.9
	Total 6.06	0.91	55.3	4.46	42	23.1	39
T_2	Grain 2.40	1.6	37.9	–	–	–	–
	Straw 3.41	0.25	6.99	–	–	–	–
	Total 5.81	0.77	44.9	–	–	–	–
T_3	Grain 2.39	1.7	40.6	–	–	–	–
	Straw 3.80	0.29	10.7	–	–	–	–
	Total 6.19	0.83	51.4	–	–	–	–
T_4	Grain 2.57	2.30	40.4	4.53	43	17.5	29
	Straw 3.62	0.22	9.61	5.51	53	5.05	8.4
	Total 6.19	0.81	50.0	5.02	43	22.5	38

3. RESULTS

3.1. Field experiment

3.1.1. Year 1, growing season 1, wheat

The grain and straw yields of wheat ranged between 2.40 and 2.57 and 3.4 to 3.8 Mg ha^{-1}, respectively (Table II). As expected, there were no significant differences in wheat yields among the treatments as all the received the same rate of N fertilizer (60 kg N ha^{-1}). The ^{15}N data revealed significant labelling of the plant material. In treatment T_1, 41 and 44% of N was derived from fertilizer in wheat grain and straw, respectively, as indicated by enrichments 4.33 and 4.59% ^{15}N a.e., fertilizer enrichment having been 10.48% ^{15}N a.e. The %N recovery values for treatments T_1 and T_4 were 39 and 38%, respectively. Total N yields in the four treatments varied from 44.9 to 55.3 kg ha^{-1}.

3.1.2. Year 1 growing season 2, rice

Both grain and straw yields increased significantly in treatment T_2 where ^{15}N-labelled crop residue was applied at 5 Mg ha^{-1}. Treatments T_1, T_3 and T_4 produced almost identical yields, with no significant differences among them (Table III).

Treatments had no significant effects on N content of plant parts or of whole plants (Table III). However, total N yield ranged between 108 and 156 kg ha^{-1} on a whole-plant basis, and was highest with treatment T_2. The weighted average values of %N derived from labelled residues (Ndfr) were 5.7, 1.7 and 6.4 in treatments T_1, T_2 and T_4, respectively. Values for labelled residue and residual fertilizer N yield were 6.98, 2.58 and 7.36 kg ha^{-1} in these treatments, respectively.

3.1.2.1. Total N and ^{15}N in soil

Values for total N and ^{15}N in soil immediately after application of ^{15}N fertilizer and also at harvest of wheat were largely similar for the various treatments (Table IV). The N-content values decreased after the harvest of rice (Table V). The rice was grown under submerged conditions, and it is likely that more N was taken up by the crop and that there was also loss due to dilution effects. The soil N contents decreased with depth.

Table III. Total N and ^{15}N derived data for rice (year 1, growing season 2)

Treatment	Plant part (Mg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	%NdfR[a]	Residue N yield (kg ha^{-1})	% N recov.
T_1	Grain 4.56	1.4	61.6	0.621	5.9	3.65	6.1
	Straw 6.31	0.98	61.8	0.564	5.4	3.33	5.6
	Total 10.9	1.1	123	0.593	5.7	6.98	12
T_2	Grain 5.91	1.3	76.8	0.182	1.7	1.34	2.2
	Straw 8.06	0.98	79.0	0.165	1.6	1.24	2.1
	Total 14.0	1.1	156	0.174	1.7	2.58	4.3
T_3	Grain 4.33	1.3	55.0	–	–	–	–
	Straw 5.88	0.90	52.9	–	–	–	–
	Total 10.2	1.1	108	–	–	–	–
T_4	Grain 4.72	1.2	57.6	0.653	6.2	3.59	6.0
	Straw 6.41	0.9	57.7	0.684	6.5	3.77	6.3
	Total 11.1	1.0	115	0.669	6.4	7.36	12

[a]Nitrogen derived from labelled wheat residue.

Table IV. Total N and ^{15}N a.e. in the soil (year 1, growing season 1, wheat)

Treatment	Soil depth (cm)	After first application of ^{15}N fertilizer at wheat sowing				At wheat harvest			
		%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})
T_1	0–15	0.09	1,863	0.205	36.4	0.06	1,242	0.23	27.3
	15–30	0.04	792	*[a]	*	0.05	990	0.03	2.83
	30–50	0.03	798	*	*	0.04	1,064	0.02	2.03
T_2	0–15	0.09	1,863	–	–	0.09	1,864	–	–
	15–30	0.05	990	–	–	0.05	990	–	–
	30–50	0.04	1,064	–	–	0.05	1,330	–	–
T_3	0–15	0.08	1,656	–	–	0.07	1,449	–	–
	15–30	0.04	792	–	–	0.06	1,188	–	–
	30–50	0.03	798	–	–	0.04	1,064	–	–
T_4	0–15	0.09	1,863	0.255	45.33	0.07	1,449	0.16	22.1
	15–30	0.04	792	*		0.05	990	0.04	3.78
	30–50	0.04	1,064	*		0.04	1,064	0.03	3.05

[a]Insufficient N for ^{15}N measurement.

Table V. Total N and ^{15}N a.e. in the soil (year 1, growing season 2, rice)

Treatment	Soil depth (cm)	At rice transplanting				At rice harvest			
		%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})
T_1	0–15	0.08	1,656	0.23	36.3	0.07	1,449	0.360	49.8
	15–30	0.04	792	0.03	2.27	0.03	594	0.016	0.91
	30–50	0.03	798	0.02	1.52	0.03	798	0.012	0.91
T_2[a]	0–15	0.07	1,449	0.122	18.3	0.08	1,656	0.11	17.4
	15–30	0.04	792	0.021	1.80	0.03	594	0.04	2.27
	30–50	0.04	1,064	0.038	4.33	0.03	798	0.02	1.52
T_3	0–15	0.08	1,656	–	–	0.07	1,449	–	–
	15–30	0.04	792	–	–	0.04	792	–	–
	30–50	0.03	798	–	–	0.03	798	–	–
T_4	0–15	0.07	1,449	0.16	22.1	0.07	1,449	0.283	39.1
	15–30	0.05	990	0.04	3.78	0.02	396	*[b]	*
	30–50	0.04	1,064	0.03	3.05	0.02	532	*	*

[a]The ^{15}N data are values after incorporation of ^{15}N-labelled wheat residue.
[b]Insufficient N for ^{15}N measurement.

Immediately after application of ^{15}N fertilizer at seeding of wheat, only 0.205 and 0.255% ^{15}N a.e. was traced at the 0- to 15-cm depth in T_1 and T_4, respectively. At harvest, % ^{15}N a.e. values at 0 to 15 cm were 0.23 and 0.16 in these treatments. Immediately after incorporation of labelled residues in rice, ^{15}N a.e. was detected in the 0- 15-cm layer in treatments T_1, T_2 and T_4. Mineralization of N from ^{15}N-labelled residues was not evident, however; there may have been preferential utilization by microorganisms of N released from living roots than from ^{15}N-labelled plant residues [3].

3.1.2.2. Soil organic matter status

As expected, after the harvest of the two crops in the first year, no significant changes were observed in the SOM content (Table VI). It was usually higher in the 0- to 15-cm layer and decreased with depth. It has, however, been reported that SOM declines rapidly in tropical and sub-tropical soils when they are cultivated continuously [4].

3.1.3. Year 2, growing season 1, wheat

Highest grain yields of wheat were recorded in treatments T_1 and T_2 where rice residues from treatment T_3 were applied (Table VII). The grain yields were considerably lower in T_3 and T_4 where normal fertilizer was applied. Only 60 kg N ha^{-1} was applied in these treatments, which is below the standard dose. The straw yields were similar and no significant differences were observed.

Table VI. SOM content after wheat (growing season 1) and rice (growing season 2) in year 1

Treatment	Soil depth (cm)	Soil organic matter		
		At initiation of expt.	After harvest of 1st crop, wheat	After harvest of 2nd crop, rice
		(%)		
T_1	0–15	1.2	1.4	1.4
	15–30	0.64	0.57	0.71
	30–50	0.50	0.48	0.72
T_2	0–15	1.2	1.5	1.4
	15–30	0.64	0.74	0.74
	30–50	0.50	0.62	0.55
T_3	0–15	1.2	1.0	1.4
	15–30	0.64	0.72	0.64
	30–50	0.50	0.59	0.55
T_4	0–15	1.2	1.2	1.4
	15–30	0.64	0.67	0.69
	30–50	0.50	0.71	0.57

Table VII. Wheat yield, total N, N derived from residues and N recovery (year 2, growing season 1)

Treatment	Plant part (Mg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	%NdfR	NdfR (kg ha^{-1})	% N recovery
T_1	Grain 2,251	2.28	51.3	0.122	1.16	0.60	1.00
	Straw 3,432	0.33	11.3	0.115	1.10	0.12	0.20
	Total 5,683	1.10	62.7	0.119	1.15	0.72	1.20
T_2	Grain 2,672	2.25	60.1	0.056	0.53	0.32	0.53
	Straw 3,251	0.34	11.1	0.049	0.47	0.05	0.08
	Total 5,923	1.20	71.2	0.053	0.51	0.37	0.61
T_3	Grain 1,694	1.74	29.5	–	–	–	–
	Straw 3,501	0.25	08.75	–	–	–	–
	Total 5,195	0.74	38.2	–	–	–	–
T_4	Grain 1,772	2.17	38.5	0.155	1.48	0.57	0.95
	Straw 3,152	0.29	09.14	0.137	1.31	0.12	0.20
	Total 4,924	0.96	47.6	0.146	1.45	0.69	1.15

Highest total N values were recorded with T_2 (71.2 kg ha^{-1}) followed by T_1 (62.6 kg ha^{-1}). The %N derived from crop residues (NdfR) value was higher in T_4, whereas the quantitative value (kg ha^{-1}) for NdfR was higher in T_1 (Table VII). The ^{15}N-labelled residue contributed 0.72, 0.37 and 0.69 kg ha^{-1} in T_1, T_2 and T_4, respectively—much less compared to the values obtained in rice of the previous year (year 1, growing season 2). Percent N recovery values for the application of 60 kg N ha^{-1} were 1.20, 0.61 and 1.15 in treatments T_1, T_2 and T_4, respectively.

3.1.4. Year 2, growing season 2, rice

Table VIII shows that yields of grain and straw were similar in all treatments except T_4, which did not receive crop residues. Highest total-N values were recorded for T_1 and T_2 (117 and 116 kg ha^{-1}, respectively). Application of ^{15}N-labelled crop residues contributed 1.35 and 0.99 kg N ha^{-1} to the total N pools in T_1 and T_2, respectively. The residual effect of N fertilizer and the removal by crop residues in T_4 was only 0.91 kg ha^{-1}. The %N recoveries were 2.3, 1.7 and 1.5 in treatments T_1, T_2 and T_4, respectively (Table VIII).

3.1.4.1. Total N and ^{15}N in soil

The data on total N and ^{15}N remaining in the soil after the harvest of wheat (year 2, growing season 1) and rice (year 2, growing season 2) are presented in Table IX. Total-N data did not show a decreasing trend with depth; lower values were recorded in the 15- to 30-cm layer. Fertilizer N either from application of ^{15}N-labelled ammonium sulphate applied at the beginning of the experiment or from the labelled crop residues showed higher values in the top 0 to 15 cm, both with wheat and with rice. However, in the case of rice, the values were much lower; fertilizer-N values were much lower at 15 cm and deeper, both with wheat and rice.

3.1.4.2. Soil Organic Matter (SOM)

Soil organic matter content data after the harvest of wheat (year 2, growing season 1) and rice (year 2, growing season 2) are shown in Table X. Organic matter showed higher values immediately after the harvest of wheat compared to rice, which was grown in the early monsoon season under submerged conditions. Samples taken immediately after harvest of wheat might have contained undecomposed residues that contributed to higher values. The SOM values were consistently higher in the surface 0 to 15 cm.

Table VIII. Rice yield, total N, N derived from residues and N recovery (year 2, growing season)

Treatment	Plant part (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	%NdfR	NdfR (kg ha^{-1})	% N recovery
T_1	Grain 4,533	1.4	61.7	0.119	1.1	0.70	1.2
	Straw 6,661	0.83	55.3	0.124	1.2	0.65	1.1
	Total 10,994	1.0	117	0.121	1.2	1.35	2.3
T_2	Grain 4,402	1.4	60.8	0.102	0.97	0.59	0.98
	Straw 7,221	0.77	55.6	0.075	0.72	0.40	0.67
	Total 11,623	1.0	116	0.089	0.85	0.99	1.7
T_3	Grain 4,603	1.1	52.5	–	–	–	–
	Straw 6,442	0.68	43.8	–	–	–	–
	Total 11,045	0.87	96.3	–	–	–	–
T_4	Grain 4,221	1.3	55.7	0.094	0.90	0.50	0.83
	Straw 5,993	0.79	42.6	0.102	0.97	0.41	0.68
	Total 10,214	1.0	98.3	0.098	0.93	0.91	1.5

Table IX. Total N and ^{15}Na.e. in soil after harvest of wheat (year 2, growing season 1) and rice (year 2, growing season 2)

Treatment	Soil depth (cm)	Wheat %N	Wheat Total N (kg ha^{-1})	Wheat % ^{15}N a.e.	Wheat ^{15}N (kg ha^{-1})	Rice %N	Rice Total N (kg ha^{-1})	Rice %^{15}N a.e.	Rice ^{15}N (kg ha^{-1})
T_1	0–15	0.093	1,925	0.109	20.0	0.050	1,035	0.094	9.28
	15–30	0.038	752	0.012	0.86	0.035	693	0.013	0.86
	30–50	0.068	1,809	0.006	1.04	0.035	931	0.011	0.98
T_2	0–15	0.073	1511	0.125	18.0	0.070	1,449	0.058	8.02
	15–30	0.035	693	0.073	4.83	0.050	990	0.004	0.38
	30–50	0.060	1,596	0.033	5.02	0.053	1,410	0.003	0.40
T_3	0–15	0.072	1490	–	–	0.068	1408	–	–
	15–30	0.032	634	–	–	0.043	851	–	–
	30–50	0.058	1543	–	–	0.037	984	–	–
T_4	0–15	0.075	1553	0.147	21.8	0.068	1,408	0.148	19.87
	15–30	0.030	594	0.024	1.36	0.040	792	0.017	1.28
	30–50	0.043	1144	0.014	1.53	0.038	1,011	0.016	1.54

Table X. Soil organic matter content after the harvest of wheat (year 2, growing season 1), rice (year 2, growing season 2) and wheat (year 3, growing season 1)

Treatment	Soil depth (cm)	Soil organic matter (%) Before experiment	After harvest of wheat	After harvest of rice	After harvest of wheat
T_1	0–15	1.4	1.4	1.1	1.6
	15–30	0.71	0.82	0.69	0.72
	30–50	0.72	0.79	0.61	0.69
T2	0–15	1.4	1.4	1.6	1.6
	15–30	0.74	0.79	0.82	0.85
	30–50	0.55	0.69	0.71	0.59
T3	0–15	1.4	1.5	1.1	1.4
	15–30	0.64	0.74	0.75	0.77
	30–50	0.55	0.80	0.61	0.55
T4	0–15	1.4	1.5	1.0	1.5
	15–30	0.69	0.68	0.73	0.63
	30–50	0.57	0.72	0.68	0.59

3.1.5. Year 3, growing season 1, wheat

The grain and straw yields of wheat and their total N contents are shown Table XI. As expected, neither grain nor straw yields of different treatments were statistically different from each other. Total N varied from 59.4 to 69.2 kg ha^{-1}, similar to those recorded in the previous year. The %NdfR data were similar in T_1 and T_4 (~0.35 kg ha^{-1}) and considerably lower in T_2 (0.15 kg ha^{-1}). The %N recovery values for the 60 kg N ha^{-1} application were only 0.61, 0.25 and 0.60 in T_1, T_2 and T_4.

3.1.6. Year 3, growing season 2, rice

Table XII shows that grain and straw yields were similar for all the treatments except T_2, which, with ^{15}N-labelled crop residues applied at 5 Mg ha^{-1}, gave the highest values. The highest total N value was also recorded in T_2 (96.6 kg N ha^{-1}). Percent NdfR values were a little higher than those observed in wheat. Application of ^{15}N-labelled crop residues contributed 0.61 and 0.39 kg ha^{-1} to the total N pool in T_1 and T_2, respectively. The residual effect of N fertilizer, and the removal by crop residues, in T_4 was only 0.49 kg ha^{-1}. The %N recovery was 1.02, 0.65 and 0.84 for T_1, T_2 and T_4, respectively.

3.1.6.1. Total N, ^{15}N and mineral N in soil

Table XIII provides data for total N and ^{15}N remaining in soil after the harvests of wheat (year 3, growing season 1) and rice (year 3, growing season 2). Total N (kg ha^{-1}) values were similar across the treatments. Comparatively higher ^{15}N values (kg ha^{-1}) were present in the top 0 to 15 cm of soil both in wheat and in rice. The amounts of mineral N, i.e. NH_4 and NO_3, were higher in T_3 and T_4 compared to the other treatments (Table XIV). Mineral N was always higher in the top soil (0–15 cm).

Table XI. Wheat yield, total N, N derived from residues and N recovery (year 3, growing season 1)

Treatment	Plant part (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	%NdfR	NdfR (kg ha^{-1})	% N recovery
T_1	Grain 2,631	1.7	44.7	0.058	0.55	0.25	0.42
	Straw 4,831	0.42	20.3	0.053	0.51	0.10	0.17
	Total 7,462	0.87	65.0	0.056	0.54	0.35	0.58
T_2	Grain 2,953	1.6	47.5	0.025	0.24	0.11	0.18
	Straw 4,503	0.40	18.0	0.022	0.21	0.04	0.07
	Total 7,456	0.88	65.6	0.023	0.23	0.15	0.25
T_3	Grain 2,982	1.7	51.6	–	–	–	–
	Straw 4,502	0.39	17.6	–	–	–	–
	Total 7,484	0.92	69.2	–	–	–	–
T_4	Grain 2,634	1.7	44.8	0.060	0.57	0.26	0.43
	Straw 4,433	0.33	14.6	0.059	0.56	0.08	0.13
	Total 7,065	0.84	59.4	0.060	0.57	0.34	0.57

Table XII. Rice yield, total N, N derived from residues and N recovery (year 3, growing season 2)

Treatment	Plant part (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	%NdfR	NdfR (kg ha^{-1})	% N recovery
T_1	Grain 4,826	0.97	44.8	0.08	0.76	0.34	0.57
	Straw 6,158	0.66	40.6	0.07	0.67	0.27	0.45
	Total 10,984	0.80	87.5	0.075	0.70	0.61	1.02
T_2	Grain 5,164	0.95	49.1	0.04	0.38	0.19	0.33
	Straw 7,430	0.64	47.6	0.04	0.38	0.18	0.32
	Total 12,594	0.77	96.6	0.04	0.38	0.39	0.65
T_3	Grain 4,729	0.97	45.9	–	–	–	–
	Straw 6,733	0.64	43.1	–	–	–	–
	Total 11,462	0.78	89.0	–	–	–	–
T_4	Grain 4,724	0.93	43.9	0.05	0.48	0.21	0.35
	Straw 6,090	0.65	40.0	0.07	0.67	0.27	0.45
	Total 10,814	0.77	83.5	0.06	0.57	0.48	0.80

Table XIII. Total N and ^{15}N a.e. in soil after harvest of wheat (year 3, growing season 1) and rice (year 3, growing season 2)

Treatment	Soil depth (cm)	Wheat				Rice			
		%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})
T_1	0–15	0.07	1,449	0.13	18.0	0.08	1,656	0.12	19.0
	15–30	0.05	990	0.07	6.61	0.04	792	0.07	5.29
	30–50	0.04	1,064	0.01	1.02	0.04	1,064	0.04	4.06
T_2	0–15	0.07	1,449	0.06	8.29	0.08	1,656	0.06	9.48
	15–30	0.03	594	0.02	1.13	0.04	792	0.03	2.27
	30–50	0.03	798	0.01	0.76	0.05	1,330	0.006	0.76
T_3	0–15	0.07	1,449	–	–	0.07	1,449	–	–
	15–30	0.06	1,188	–	–	0.04	792	–	–
	30–50	0.03	798	–	–	0.07	1,862	–	–
T_4	0–15	0.07	1,449	0.11	15.2	0.06	1,242	0.14	16.6
	15–30	0.05	990	0.04	3.78	0.04	792	0.04	3.02
	30–50	0.03	798	0.02	1.52	0.04	1,064	0.014	1.42

Table XIV. NH_4-N and NO_3-N in soil at wheat harvest (year 3, growing season 1) and rice (year 3, growing season 2)

Treatment	Soil depth (cm)	At wheat harvest		After wheat sowing		After rice harvest	
		NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
		(µg g^{-1})					
T_1	0–15	8.75	7.09	8.73	7.00	9.04	6.77
	15–30	8.76	6.33	8.69	6.75	8.61	6.35
	30–50	7.01	3.88	6.96	3.84	6.91	4.45
T_2	0–15	9.46	6.65	9.20	6.51	9.09	6.82
	15–30	8.85	6.35	9.00	6.75	8.56	6.17
	30–50	7.19	4.94	7.03	4.25	6.79	4.12
T_3	0–15	10.0	7.30	9.84	7.36	10.2	7.67
	15–30	9.08	6.79	4.41	6.49	8.58	6.38
	30–50	7.21	4.50	7.06	3.96	7.11	3.71
T_4	0–15	11.1	8.44	10.1	7.60	10.5	7.90
	15–30	8.62	6.80	8.25	6.55	9.31	6.94
	30–50	7.20	4.68	6.86	4.25	7.18	4.64

3.1.6.2. Soil Organic Matter

The values for SOM content in soil at the harvests of wheat (year 3, growing season 1) and rice (year 3, growing season 2) for the three soil depths (0–15, 15–30 and 30–50 cm) are presented in Table XV. No significant changes were recorded among the treatments, although T_1 and T_2 (with crop residues added at 5 Mg ha^{-1}) showed the higher values. The surface layer usually showed the highest %SOM values.

Table XV. Soil organic matter content at harvest of wheat (year 3, growing season 1) and rice (year 3, growing season 2)

Treatment	Soil depth (cm)	Soil organic matter		
		Before experiment	After wheat harvest	After rice harvest
		(%)		
T_1	0–15	1.36	1.58	1.91
	15–30	0.71	0.72	0.62
	30–50	0.72	0.69	0.40
T_2	0–15	1.38	1.59	1.67
	15–30	0.74	0.85	0.68
	30–50	0.55	0.59	0.36
T_3	0–15	1.36	1.39	1.55
	15–30	0.64	0.77	0.59
	30–50	0.55	0.55	0.40
T_4	0–15	1.36	1.53	1.54
	15–30	0.69	0.63	0.63
	30–50	0.57	0.59	0.36

Table XVI. Wheat yield, total N, N derived from residues and N recovery (year 4, growing season 1)

Treatment	Plant part (kg ha^{-1})	% N	Total N (kg ha^{-1})	% ^{15}N a.e.	%NdfR	NdfR (kg ha^{-1})	% N recovery
T_1	Grain 2,600	1.60	41.6	0.036	0.34	0.14	0.23
	Straw 4,600	0.30	13.1	0.032	0.31	0.04	0.07
	Total 7,200	0.77	55.4	0.034	0.32	0.18	0.30
T_2	Grain 2,789	1.62	45.2	0.020	0.19	0.09	0.15
	Straw 4,423	0.25	11.1	0.016	0.15	0.02	0.03
	Total 7,212	0.78	56.2	0.018	0.20	0.11	0.18
T_3	Grain 2,858	1.58	45.2	–	–	–	–
	Straw 4,416	0.30	13.3	–	–	–	–
	Total 7,274	0.80	58.4	–	–	–	–
T_4	Grain 2,841	1.60	45.5	0.025	0.24	0.11	0.18
	Straw 5,234	0.30	15.7	0.030	0.29	0.05	0.08
	Total 8,075	0.76	61.2	0.028	0.26	0.16	0.27

3.1.7. Year 4, growing season 1, wheat

Wheat grain and straw yields ranged between 2.60 to 2.86 and 4.4 to 5.2 Mg ha^{-1}, respectively (Table XVI). Yields varied little among the treatments and were similar to those recorded the previous year. Total N amounts were 55.4, 56.3, 58.4, and 61.2 kg ha^{-1} for T_1 to T_4, respectively. The values for percent N derived from crop residues (NdfR) were identical in T_1 and T_4, but lower in treatment T_2. Percent N recoveries were 0.32, 0.18 and 0.27 for T_1, T_2 and T_4 respectively.

Table XVII. Rice yield, total N, N derived from residues, and N recovery (year 4, growing season 2)

Treatment	Plant part (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	%NdfR	NdfR (kg ha^{-1})	% N recovery
T_1	Grain 4,950	0.80	39.6	0.0390	0.37	0.147	0.25
	Straw 6,869	0.50	34.4	0.0360	0.34	0.117	0.20
	Total 11,819	0.63	74.0	0.0375	0.36	0.264	0.44
T_2	Grain 5,471	0.83	45.4	0.0191	0.18	0.082	0.14
	Straw 7,163	0.55	39.4	0.0180	0.17	0.067	0.11
	Total 12,634	0.67	84.8	0.0185	0.18	0.149	0.25
T_3	Grain 5,275	0.81	42.7	–	–	–	–
	Straw 6,963	0.49	34.1	–	–	–	–
	Total 12,238	0.63	76.9	–	–	–	–
T_4	Grain 5,125	0.80	41.0	0.0310	0.30	0.123	0.21
	Straw 6,581	0.46	30.3	0.0300	0.28	0.085	0.14
	Total 11,706	0.61	71.3	0.0305	0.29	0.208	0.35

Table XVIII. Total N and ^{15}N a.e. in soil after the harvest of wheat (year 4, growing season 1) and rice (year 4, growing season 2)

Treatment	Soil depth (cm)	At wheat harvest				At rice harvest			
		%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})
T_1	0–15	0.065	1,346	0.074	9.50	0.10	2,070	0.084	16.59
	15–30	0.035	693	0.009	0.60	0.03	594	0.012	0.68
	30–50	0.075	1,995	0.005	0.95	0.07	1,862	0.008	1.42
T_2	0–15	0.085	1,760	0.049	8.22	0.10	2,070	0.032	6.32
	15–30	0.030	594	0.004	0.23	0.04	792	0.006	0.45
	30–50	0.077	2,048	0.003	0.59	0.06	1,596	0.004	0.61
T_3	0–15	0.07	1,449	–	–	0.07	1,449	–	–
	15–30	0.04	792	–	–	0.04	792	–	–
	30–50	0.065	1,729	–	–	0.04	1,064	–	–
T_4	0–15	0.083	1,718	0.105	17.2	0.09	1,863	0.050	8.89
	15–30	0.04	792	0.009	0.68	0.03	594	0.008	0.45
	30–50	0.032	851	0.008	0.65	0.03	798	0.008	0.61

3.1.8. Year 4, growing season 2, rice

Rice grain and straw yields ranged between 4.95 and 5.47 and 6.86 and 7.16 Mg ha^{-1}, respectively (Table XVII). All treatments showed similar total yields, with that from T_2 slightly higher. Total N content was significantly higher where ^{15}N-labelled crop residues had been applied at 5 Mg ha^{-1}, i.e. in T_2 (84.8 kg ha^{-1}), whereas with T_1, T_3 and T_4 the values were similar. The weighted average values of %N derived from labelled residues were 0.357, 0.176 and 0.291 in treatments T_1, T_2 and T_4, respectively. Values for N derived from residues (NdfR) were 0.264, 0.149 and 0.208 kg ha^{-1}, respectively.

3.1.9. Total N, ^{15}N and mineral N in soil

During the fourth year of the study, the total N, ^{15}N retained in soil, NH_4-N and NO_3-N present in the soil were determined for both the crops (Tables XVIII and XIX). In general, total N was higher in the topsoil (0–15 cm) than in the 15- to 30-cm layer. Considering the 0 to 15 cm the total N (kg ha^{-1}) ranged from 1,346 to 2,070 for both crops (Table XVIII). Fertilizer N, either by direct application of ^{15}N-labelled ammonium sulphate applied at the beginning of the experiment or as labelled crop residues, showed higher values in the surface 0 to 15 cm, both with wheat and rice. In general the NH_4-N values were higher than those for NO_3-N and the topsoil usually showed the highest values (Table XIX).

Table XIX. NH_4-N and NO_3-N in soil at the harvest of wheat (year 4, growing season 1) and of rice (year 4, growing season 2)

Treatment	Soil depth (cm)	Beginning of the expt.		After wheat harvest		After rice harvest	
		NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
		(µg g^{-1})					
T_1	0–15	8.73	7.00	8.10	6.63	8.44	6.43
	15–30	8.69	6.75	8.09	6.26	8.53	6.37
	30–50	6.96	3.84	7.06	3.98	6.89	3.89
T_2	0–15	9.20	6.51	9.05	6.79	8.83	6.68
	15–30	9.00	6.75	8.53	6.41	8.90	6.54
	30–50	7.03	4.25	7.23	3.98	7.16	3.81
T_3	0–15	9.84	7.36	9.86	7.21	9.67	7.29
	15–30	8.41	6.49	9.34	6.41	8.89	6.66
	30–50	7.06	3.96	6.96	3.69	6.89	4.17
T_4	0–15	10.1	7.60	10.6	7.21	11.0	8.03
	15–30	8.25	6.55	9.30	6.41	9.18	6.89
	30–50	6.86	4.25	6.98	3.69	6.99	4.45

Table XX. Soil Organic Matter content at the harvest of wheat (year 4, growing season 1) and rice (year 4, growing season2)

Treatment	Soil depth (cm)	Soil organic matter		
		Before the experiment	After wheat harvest	After rice harvest
		(%)		
T_1	0–15	1.5	1.5	2.1
	15–30	0.65	0.74	0.73
	30–50	0.54	0.99	0.68
T_2	0–15	1.5	1.5	2.1
	15–30	0.63	0.70	0.69
	30–50	0.64	1.5	0.73
T_3	0–15	1.3	1.3	1.9
	15–30	0.61	0.73	0.75
	30–50	0.58	0.70	0.62
T_4	0–15	0.55	1.3	1.8
	15–30	0.55	0.51	0.61
	30–50	0.66	1.02	0.73

Table XXI. Total N and ^{15}N data in soil incubated with crop residues

Treatment	Soil depth (cm)	1st sampling at 4 weeks				2nd sampling at 6 weeks			
		%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})	%N	Total N (kg ha^{-1})	% ^{15}N a.e.	^{15}N (kg ha^{-1})
R_1	0–15	0.06	1,304	0.104	12.9	0.07	1,511	0.118	17.0
	15–30	0.07	1,465	0.024	3.35	0.06	1,148	0.033	3.61
	30–50	0.09	2,261	0.024	5.18	0.08	1,995	0.012	2.28
R_2	0–15	0.07	1,346	0.126	16.2	0.07	1,346	0.086	11.1
	15–30	0.06	1,089	0.026	2.70	0.07	1,386	0.009	1.19
	30–50	0.08	1,995	0.029	5.52	0.10	2,527	0.006	1.45
R_3	0–15	0.04	828	0.077	6.08	0.04	828	0.074	5.85
	15–30	0.05	990	0.021	1.98	0.07	1,346	0.014	1.80
	30–50	0.08	2,075	0.016	3.17	0.06	1,463	0.006	0.84
R_4	0–15	0.04	849	0.121	9.80	0.06	1,242	0.027	3.20
	15–30	0.06	1,148	0.052	5.70	0.05	1,049	0.029	2.90
	30–50	0.06	1,490	0.022	3.13	0.04	1,144	0.009	0.98
		3rd sampling at 8 weeks				4th sampling at 10 weeks			
R_1	0-15	0.07	1,449	0.128	17.7	0.07	1,449	0.194	26.8
	15-30	0.06	1,188	0.104	11.8	0.07	1,307	0.033	4.12
	30-50	0.05	1,330	0.164	20.8	0.07	1,862	0.012	2.13
R_2	0-15	0.07	1,449	0.011	1.52	0.05	1,035	0.239	23.6
	15-30	0.06	1,247	0.021	2.50	0.05	1,049	0.129	12.9
	30-50	0.05	1,410	0.026	3.50	0.07	1,862	0.011	1.95
R_3	0-15	0.08	1,553	0.006	0.89	0.06	1,242	0.080	9.48
	15-30	0.08	1,485	0.007	0.99	0.06	1,188	0.077	8.73
	30-50	0.06	1,676	0.020	3.20	0.06	1,596	0.058	8.83
R_4	0-15	0.05	1,035	0.198	19.6	0.05	1,035	0.224	22.1
	15-30	0.06	1,188	0.016	1.81	0.05	990	0.069	6.52
	30-50	0.09	2,394	0.010	2.28	0.06	1,596	0.018	2.74

3.1.10. Soil organic matter

After the harvest of the two crops in the fourth year, %SOM values showed higher values immediately after harvest of rice compared to wheat (Table XX). They were also usually higher in the surface layer (0–15 cm) and in several instances the values at 15 to 30 cm were lower than those at 30 to 50 cm.

3.2. Incubation study

3.2.1. Total N and ^{15}N in soil and plant

Total N and ^{15}N values were higher in soils incubated with ^{15}N-labelled crop residues incorporated 2 weeks before planting (Table XXI). This indicated that there was more decomposition of crop residues and release of N was also higher in this treatment (R_1). Higher values of ^{15}N was recorded over at the fourth sampling at 10 weeks. Nitrogen-15 in labelled residues remained in the surface 0 to 15 cm in the PVC cylinder.

Total N and uptake by wheat of N release from crop residue are shown in Table XXII. Both total N and ^{15}N uptake were higher during the earlier stages of growth then decreased with crop development. Therefore, with the growth and development of the plant, N requirement increased and, to some extent, plants could meet their needs with N released from the crop residues. Therefore, a synchrony of N release with the crop uptake, although irregular, occurred.

3.2.2. Mineral nitrogen

Changes in soil mineral N following the addition of crop residues are shown in Table XXIII. Apparently, there was no significant difference in NH_4-N and NO_3-N mineralized either from soil or from crop residues. The proportion of mineral N was identical at all the sampling periods. It is, however, again evident that values for both NH_4-N and NO_3-N were highest at the top 0 to 15 cm and decreased with depth (cf. Table XIV).

Table XXII. Total N, ^{15}N uptake and N derived from residues by wheat in relation to release from crop residues[a]

Treatment	1st sampling, 4 wks		2nd sampling, 6 wks		3rd sampling, 8 wks		4th sampling, 10 wks	
	%N	% ^{15}N a.e.	%N	% ^{15}N a.e.	%N	% ^{15}N a.e.	%N	% ^{15}N a.e.
T1	2.8	0.181 (1.7)[b]	2.3	0.167 (1.6)	2.4	0.131 (1.3)	2.0	0.138 (1.3)
T2	2.9	0.067 (0.64)	2.5	0.094 (0.90)	2.4	0.084 (0.80)	2.0	0.066 (0.63)
T3	2.9	0.194 (1.9)	2.3	0.179 (1.7)	2.2	0.152 (1.5)	1.8	0.156 (1.5)

[a]Residue ^{15}N a.e.= 10.48%. [b]%NdfR.

Table XXIII. Nitrogen as NH_4 and NO_3 in soil under incubation during the wheat season, 1997–98

Treatment	Soil depth (cm)	1st sampling		2nd		3rd		4th		5th	
		NH_4	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4	NO_3
		($\mu g\ g^{-1}$)									
R1	0–15	9.9	7.9	9.9	7.7	9.3	7.5	9.9	7.9	9.4	7.4
	15–30	9.3	7.2	8.8	7.3	9.0	6.8	8.9	7.0	8.3	6.1
	30–50	7.1	5.2	7.7	5.5	8.2	5.4	7.4	5.0	6.8	3.8
R2	0–15	10	7.7	10	6.7	9.6	7.5	10	7.8	9.6	7.4
	15–30	9.3	7.0	8.6	7.2	8.8	6.8	8.7	6.5	8.5	6.6
	30–50	7.1	4.8	7.6	5.1	7.8	4.4	7.3	5.1	7.3	4.5
R3	0–15	11	8.2	10	7.8	10	7.4	11	7.7	11	7.6
	15–30	8.9	6.5	8.8	6.2	8.6	6.3	9.3	6.7	8.6	6.6
	30–50	7.2	4.4	7.8	5.3	7.2	4.2	7.4	4.7	7.2	4.3
R4	0–15	11	8.5	11	7.5	11	7.8	11	8.5	12	8.3
	15–30	9.6	7.1	9.2	6.5	9.0	7.0	9.3	6.7	9.1	7.1
	30–50	7.7	5.0	7.7	5.8	7.4	4.5	7.3	4.2	7.0	4.3

3.2.3. Total N and ^{15}N in soil under incubation at harvest of wheat

Total N was randomly distributed in the 0–15 cm cylinder, but ^{15}N released from labelled crop residues was always higher in the top 0-15 cm soil (Table XXIII). The highest ^{15}N was recorded with the treatment of longest incubation period. Nitrogen-15 content gradually decreased over time with shorter incubation period.

4. CONCLUSIONS

Treatments with crop residues (T_1 and T_2) generally produced higher yields than those without residues. This trend was particularly clear in the second crop (rice) for each year. The utility of labelling crop residues as well as fertilizer with ^{15}N was clear. Although ^{15}N fertilizer applied in the first crop (wheat) of year 1, was recovered in subsequent crops as was ^{15}N-labelled crop residues, most of the ^{15}N was retained in the soil and was unavailable for plant uptake.

ACKNOWLEDGMENTS

The authors are grateful to the Joint FAO/IAEA Division of the International Atomic Energy Agency, Vienna, Austria, for partial financial support and for analyses of total N and ^{15}N at the Soil Science Unit of the Agriculture and Biotechnology Laboratory at Seiborsdorf, Austria. Thanks are extended to the scientific staff of the Soil Science Division of BINA who helped in the laboratory and the field work.

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THE FATE OF ORGANIC MATTER IN A SUGARCANE SYSTEM IN BRAZIL

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Abstract

Our objective was to gain a better understanding of organic matter and nutrient turnover in the cultivation of sugarcane. Related processes that involve soil water content, soil bulk density and soil temperature, were included. A comparison was made between the traditional management practice of burning the cane trash before harvest, with the newly recommended practice of leaving the trash on the soil surface after harvest. Results showed great differences in surface-soil temperature and water content between the two management practices. Water balances were not affected, but the dynamics of nitrogen and organic matter in the soil-plant system differed significantly. The sugarcane productivity was, however, not affected by management practice, during the first 3 years of the study.

1. INTRODUCTION

Worldwide, Brazil is the largest producer of sugarcane producer. It is cultivated on over 4 Mha with a total yield of 240 Mt of cane, 9.5 Mt sugar, and 12 GL of alcohol. In general, the cropped area is submitted to straw burning before harvest, to facilitate cutting and transport operations. Recent emphasis on adopting agricultural practices, for greater sustainability of the system, is exerting pressure on this agroindustry to review management procedures, including consideration of harvesting without previous burning, called “raw-cane harvest” or “green-cane harvest.” With the new approach, straw and tips, jointly called trash, are chopped and left on the soil surface after harvest, thus mulching the next ratoon crop.

The practice of burning the cane straw presents mostly economic advantages, facilitating manual harvesting by cutters who are paid on a t day^{-1} basis. Furthermore, the maintenance of all organic matter in the system can lead to advantages for the soil, will reduce air pollution (CO_2 and wind-carried ash) and, probably, will reduce the need for mineral fertilizers.

The green-cane method was recently adopted in the main sugarcane-producing areas of Brazil. Therefore, it is fundamentally important to understand how this new practice will affect nutrient dynamics in order to maximize its positive aspects and improve sustainability. For these reasons, this agroindustrial problem was chosen to be part of the FAO/IAEA Co-ordinated Research Project on “The use of isotope techniques in studies on the management of organic matter and nutrient turnover for increased, sustainable agricultural production and environmental preservation.”

The main objectives of the project were:

- to review the state-of-the-art on soil organic matter studies,
- to discuss how the decomposition of organic matter in tropical soils affects nutrient release and soil physical/chemical properties,
- to determine factors that control nutrient losses from decomposing organic matter, and to seek management options to increase the use efficiency of the released nutrients by the crop, and
- to examine how computer-simulation models can play a role in predicting optimal organic matter levels.

These objectives fitted exactly the described sugarcane-management situation in Brazil.

2. DESCRIPTION OF THE EXPERIMENT

Sugarcane, a semi-perennial crop that is replanted every 5 to 8 years, belongs to the grass family (Gramineae). Cane stalks can reach 3 m height. It has a bulky rhizome, and the root system is confined mostly within the 0.5-m topsoil, although some roots grow more deeply than 1 m. It is planted in rows and harvested after 1 year or more. Stalks are used to manufacture sugar and/or alcohol. After each harvest, the rhizome sprouts, renewing the crop: the ratoon. After four to seven ratoons, the crop is renewed with stalk cuttings.

This experiment was started in October 1997, on a Dark Red Latosol (Rhodic Kandiudalf), locally called "Terra Roxa Estruturada," at Piracicaba (22°42' S, 47°38' W) in the State of São Paulo, Brazil, at 580 m above sea level and 250 km inside the continent. The medium/late sugarcane variety SP 80-3280 was planted on 0.21 ha, i.e., fifteen rows 100 m long, spaced 1.4 m, as illustrated in Fig. 1. Four treatments with four replicates each were imposed on the central lines (7, 8 and 9), called upper, central and lower, due to a 7.4% slope, separated by borders, in such a way that each plot had three cane rows of 4 m, totalling 16.8 m^2. Figure 1 also shows three transects of 84 m each, consisting of 1-m plots used for geostatistical and state-space analysis [1]. The experimental scheme extended over a period of 5 years, as follows: (i) October 1997 to October 1998, planted crop; (ii) October 1998 to October 1999, first ratoon crop; (iii) October 1999 to October 2000, second ratoon; (iv) October 2000 to October 2001, third ratoon; (v) October 2001 to October 2002, fourth ratoon crop. This report presents data for the period 1997 to 2000.

During the first year (1997–1998), no treatments were imposed; the field was managed homogeneously according to traditional agricultural practices. After the October-1998 harvest, treatments were applied to the crop as indicated in Fig. 1.

Treatment T_1 consisted of "green-cane harvest" with mulching. At planting time (October 1997), the crop was fertilized with 63 kg ha^{-1} of ^{15}N-labelled ammonium sulphate, and after the first harvest (October 1998) received non-labelled trash from T_2.

Treatment T_2 also consisted of "green-cane harvest" with mulching. The same N application rate as T_1 was applied at planting time (October 1997), however it was not labelled. After the first harvest (October 1998) it received ^{15}N-labelled trash mulch from T_1.

Treatment T_3 consisted of "green-cane harvest with bare interrow." All crop residues were exported, leaving bare interrow areas. All other management practices were the same as for T_1 and T_2.

Treatment T_4 consisted of "burning straw before harvest". This treatment also received ^{15}N-labelled trash in October 1997, as for T_1.

Phosphorus and K fertilization, and all other management practices adopted during cane development, were the same for all treatments. Only one ^{15}N-labelled fertilizer pulse was applied, in October 1997, with the objective of following its fate over the 5-year period, in plant and soil, in order to better understand the organic matter flow in these management systems.

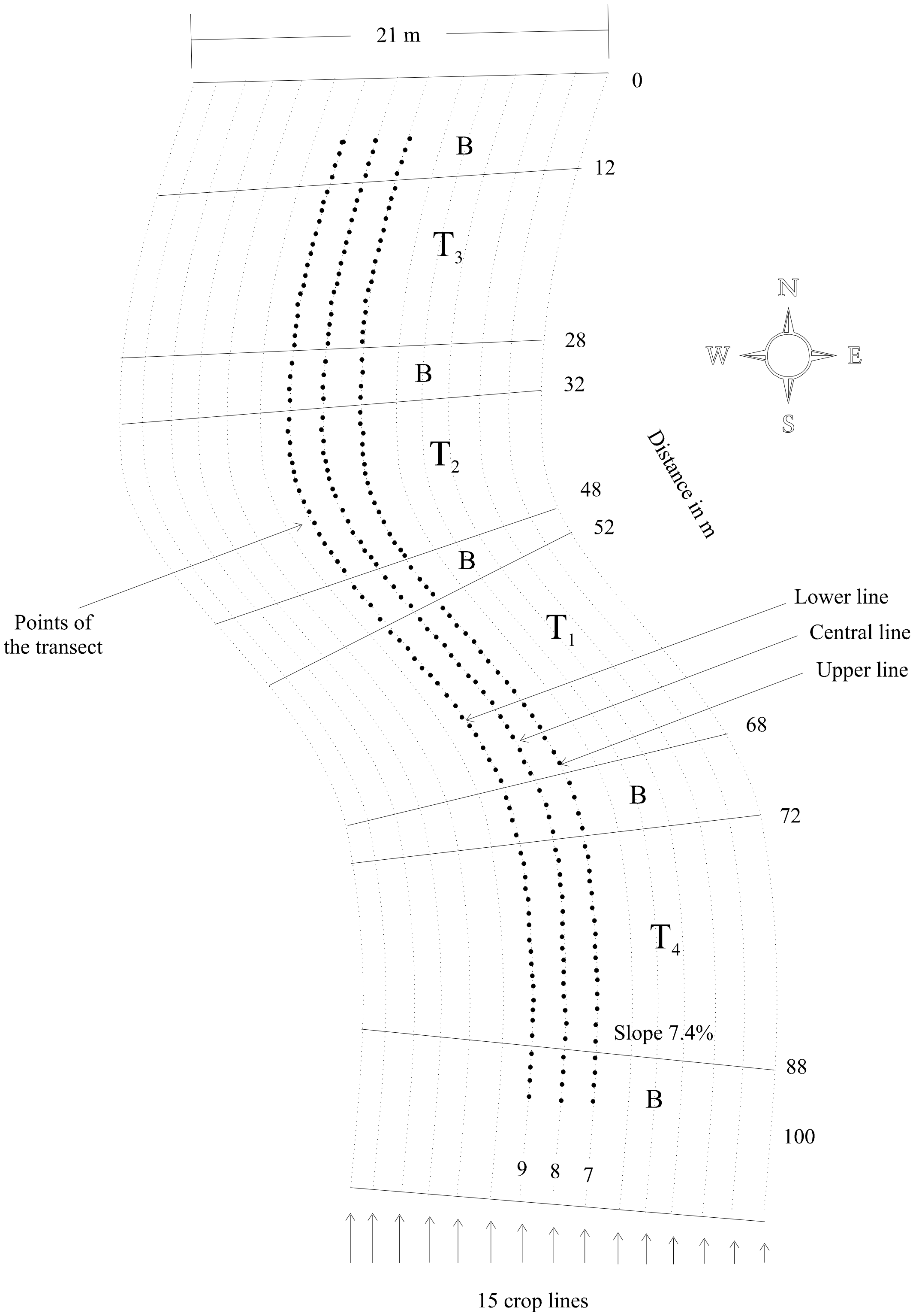

FIG. 1. Schematic view of the experimental area. Treatments T_1 and T_2 were mulched, T_3 had bare interrow, and T_4 had burned trash after harvest. B=borders.

The following aspects were studied:

- Soil Chemistry: soil organic matter (SOM) including its fractionation according to particle-size distribution, and respective ^{15}N enrichment. Soil properties: pH, SOM, P, K, Ca, Mg, H^+, Al, SB, T, and V;
- Soil Physics: temperature, water content, water storage, water-balance components, and compaction evaluated through bulk density measurements;
- Plant Development: plant ^{15}N enrichment during growth, and, at harvest, number of canes m^{-1}, weight of canes, weight of straw, weight of tips.

3. RESULTS AND DISCUSSION

3.1. Soil water content and temperature

A state-space approach was used [2] to investigate the effects of organic-matter mulching on soil water content and temperature. Water-content and temperature data were collected along the 84-point transect (Fig. 2). The temperature data reflect visually the effects of the treatments on the average soil temperature of the surface layer (0.03 to 0.09 m). Treatments T_1 and T_2 presented much lower temperatures (overall average of 23.2°C) due to the presence of the mulch (trash = tips + straw, 127 kg ha^{-1} of dry matter); T_3, with the soil surface bare, presented an average of 30.1°C; and T_4, the burned treatment, had an average of 28.3°C. These differences in temperature were due to the fact that they were measured two weeks after harvest of the first crop, when the ratoon crop was starting to sprout and the soil was exposed to sunshine (November 20, 1998, a late spring day) after six days without rainfall.

Soil water content data (0–0.2 m layer), collected on the same day, presented an inverse pattern. The mulched treatments, T_1 and T_2, showed higher water contents in relation to the bare T_3 and the burned T_4 treatments. This is demonstrated in Fig. 3, which shows a correlation (R^2 = 0.4491, significant at the 5% level) between soil temperature T and soil water content θ. The negative slope of the relation expresses the inverse relation between T and θ.

The state-space analyses applied to soil water content and temperature are presented in Figs. 4 and 5, respectively, after transforming the data according to [3]. The obtained matrix coefficients were:

$$\theta_i = 0.881\ \theta_{i-1} + 0.1148\ T_{i-1} + W_{\theta i} \qquad (1)$$

$$T_i = 0.0615\ \theta_{i-1} + 0.9272\ T_{i-1} + W_{Ti} \qquad (2)$$

The shaded area of Figs. 4 and 5 represent the fiducial limits considering ± one standard deviation. Analyzing Eqq. (1) and (2), it can be seen that θ at location i-1 contributed 88% to the estimate of θ in i, while T at i-1 contributed with 11.5%, showing that the contribution of θ of the first neighbour was more significant than that of T.

For the case of temperature estimation (Fig. 5), Eq. (2) shows that θ_{i-1} contributed with 6.2% in the estimate of the temperature at point i. On the other hand, T_{i-1} contributed with 93%. This state-space analysis is the first performed on soil spatial data in Brazil. One objective was its introduction into the Brazilian literature and, as already said, to contribute to a better understanding of the relation between θ and T.

Relating soil properties at sites i to properties at sites i-h is also of practical importance, mainly to farmers. In this study, the lag of 1 m was small for practical purposes, however it is very important to better understand how far one property is affected by its neighbour, and so recognize management practices that would lead to increased yield. Precision agriculture is one of the recent fields that contributes to these aspects.

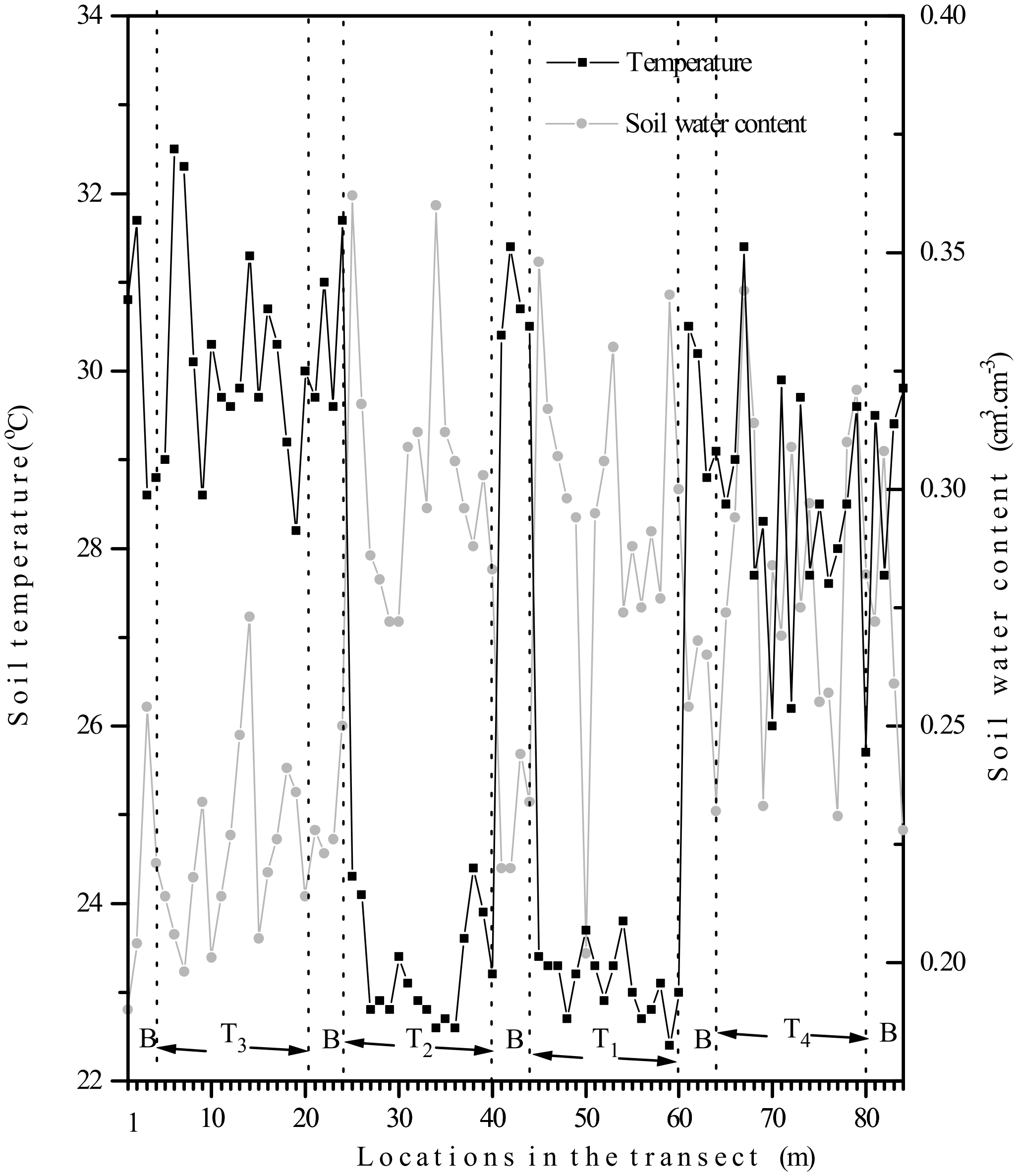

FIG. 2. Distributions of soil temperature (average of three depths: 0.03, 0.06, and 0.09 m) and water content (0–0.20 m) meter by meter along the 84-point transect, at noon (11:00 AM–12:00) on Nov. 20, 1998. B=border; T_1 and T_2=trash mulching; T_3=bare soil; T_4=burned trash.

Analysis of variance was used to compare average values of soil temperature. The differences between mulched (T_1 and T_2) and non-mulched (T_3 and T_4) treatments were significant for the average temperature at all measured depths (0.03–0.09 m layer), even at the greatest depth, as shown in Fig. 6. Between mulched treatments (T_1 and T_2) the difference was not significant (Table I, November 18, 1998).

For this early date, when the crop covered no more than 10% of soil surface, the burned trash in T_4 significantly affected soil temperatures as compared to the bare soil of T_3 The situation on December 12, 1998, was very similar but there was no difference between T_3 and T_4, indicating that there was no more effect of the residues of the burned trash. On December 18, 1998, a cloudy day, the significant differences shown in Table I have no physical meaning since the average values are very close.

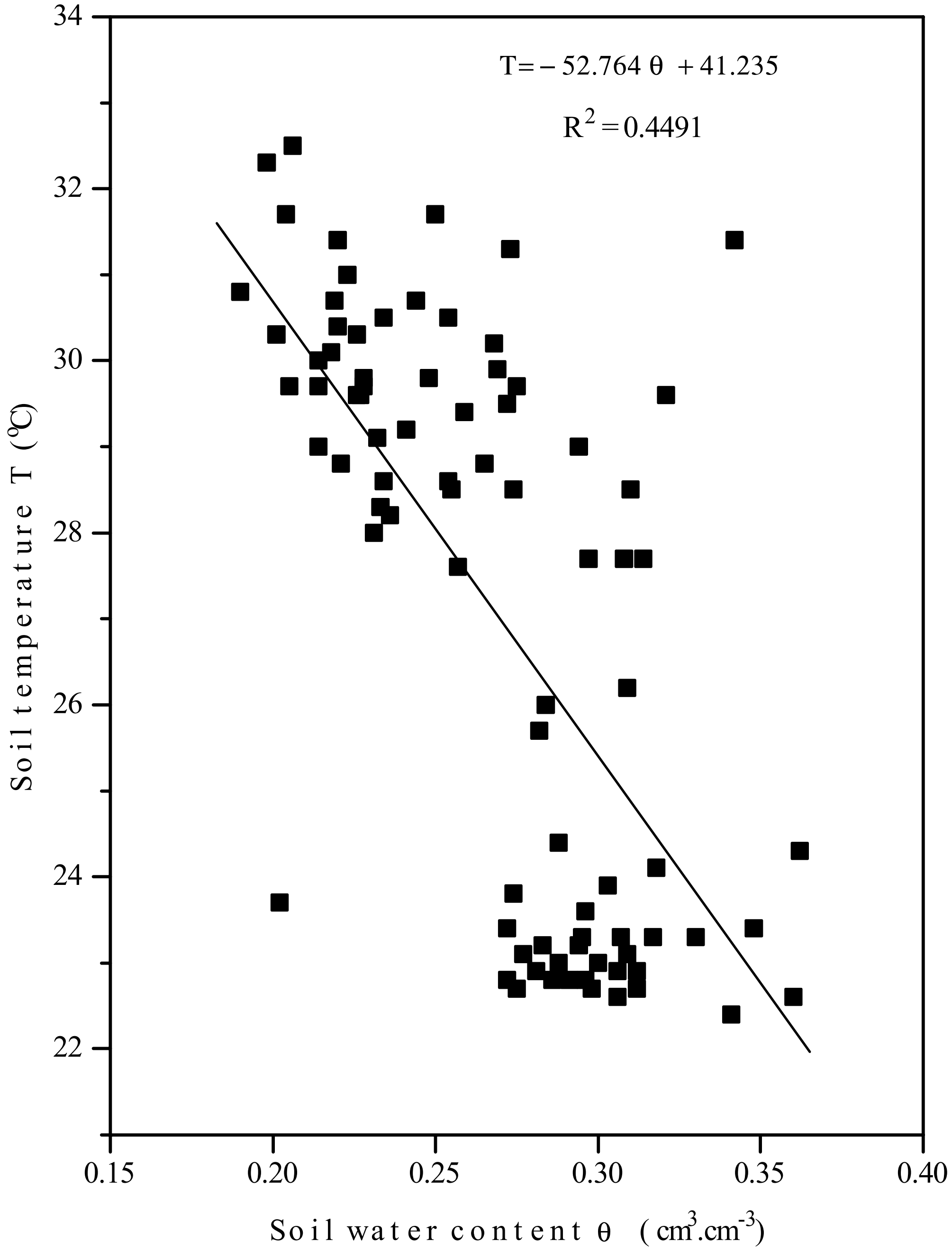

FIG. 3. Correlation between soil-temperature and water-content data of Fig. 2.

The data of January 12, 1999, were collected when the plants were about 1-m tall. Although Table I indicates no differences among T_1, T_2 and T_3, the average temperature of the bare treatment T_3 was slightly higher than that of the mulched treatments, T_1 and T_2, at least for depths of 0.06 and 0.09 m. The greater difference between these treatments and T_4 is likely due to a delay in plant growth for the burned trash treatment. On February 5, 1999 (also a cloudy day), the differences shown in Table II had no physical significance. The same can be said for the other dates (March 4, April 7, May 14 and June 29), which were not cloudy. On the last date, the plant canopy completely shaded the interrows, therefore treatments no longer affected soil temperature. The slightly higher temperatures at the beginning of the transect (0–15 m) on June 29 were due to clearings from wind-fallen canes.

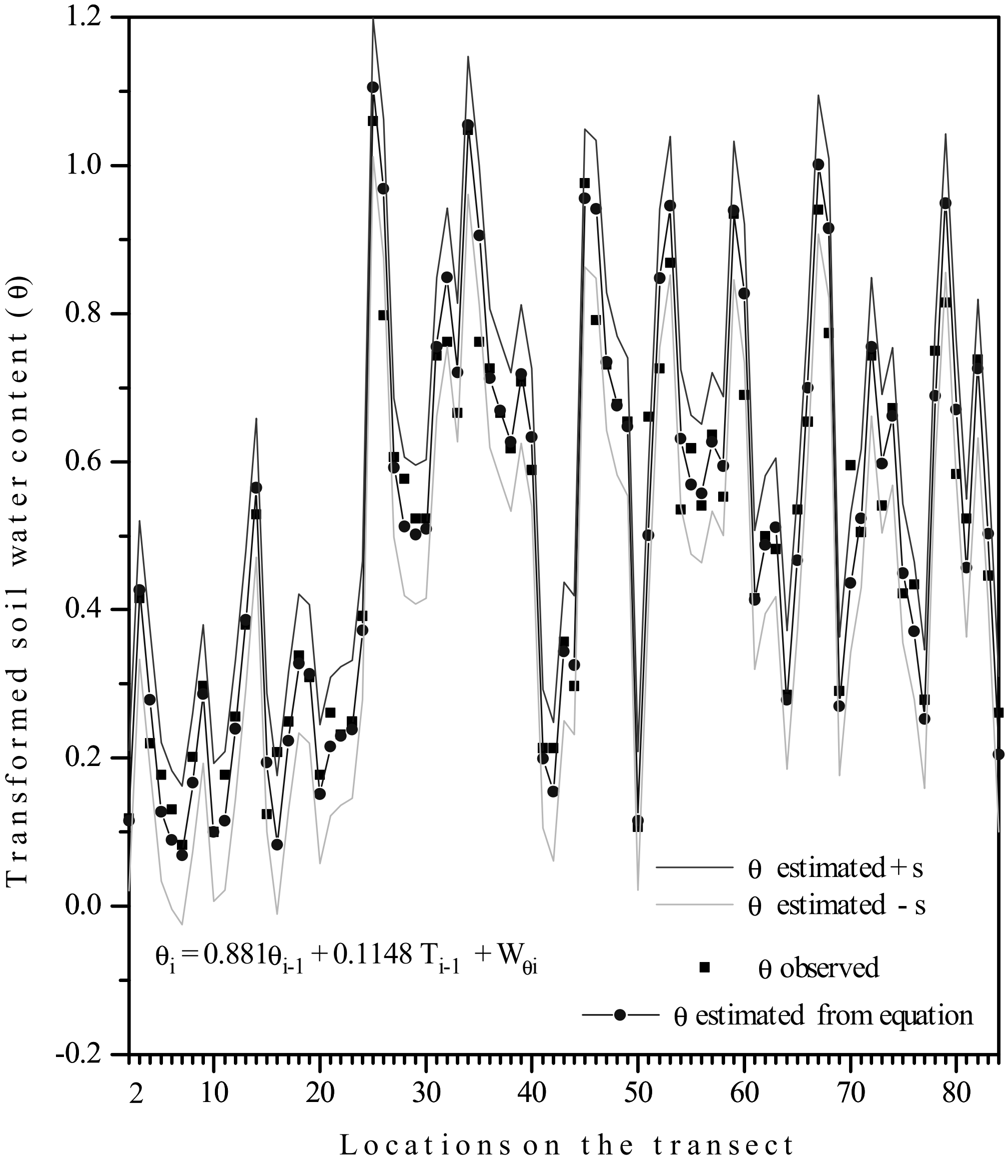

FIG 4. State-space analysis of transformed soil water content θ data of Fig. 2, using the transformation: $x_i = [X_i - (m - 2s)]/4s$.

The temperature differences between the non-mulched treatments (T_3 and T_4) and the mulched (T_1 and T_2) reached 7°C in November, decreasing to almost zero in February (Table I). Peak values, at the shallow depth (0.03 m), reached 37°C, and, since soil-temperature profiles, are, in general, exponential, the soil surface must have reached much higher temperatures. The spring-summer period is very important for the establishment of ratoon crops, and it was expected that lower soil temperatures due to mulching would favour development. During this relatively short period in the crop cycle, the young rhizome is more sensitive to high temperatures. Yield data (Table II) show, however, a negative effect of the mulch on growth, since at harvest (October 1999) T_1 and T_2 had significantly lower values for wet mass and number of stalks per meter of row, in relation to T_3 and T_4, except for the number of stalks in T_4. A humid microenvironment in the straw layer, which had a thickness, initially, of 0.20 to 0.30 m, may have promoted the growth of fungi and microorganisms, affecting rhizome sprouting and stalk development.

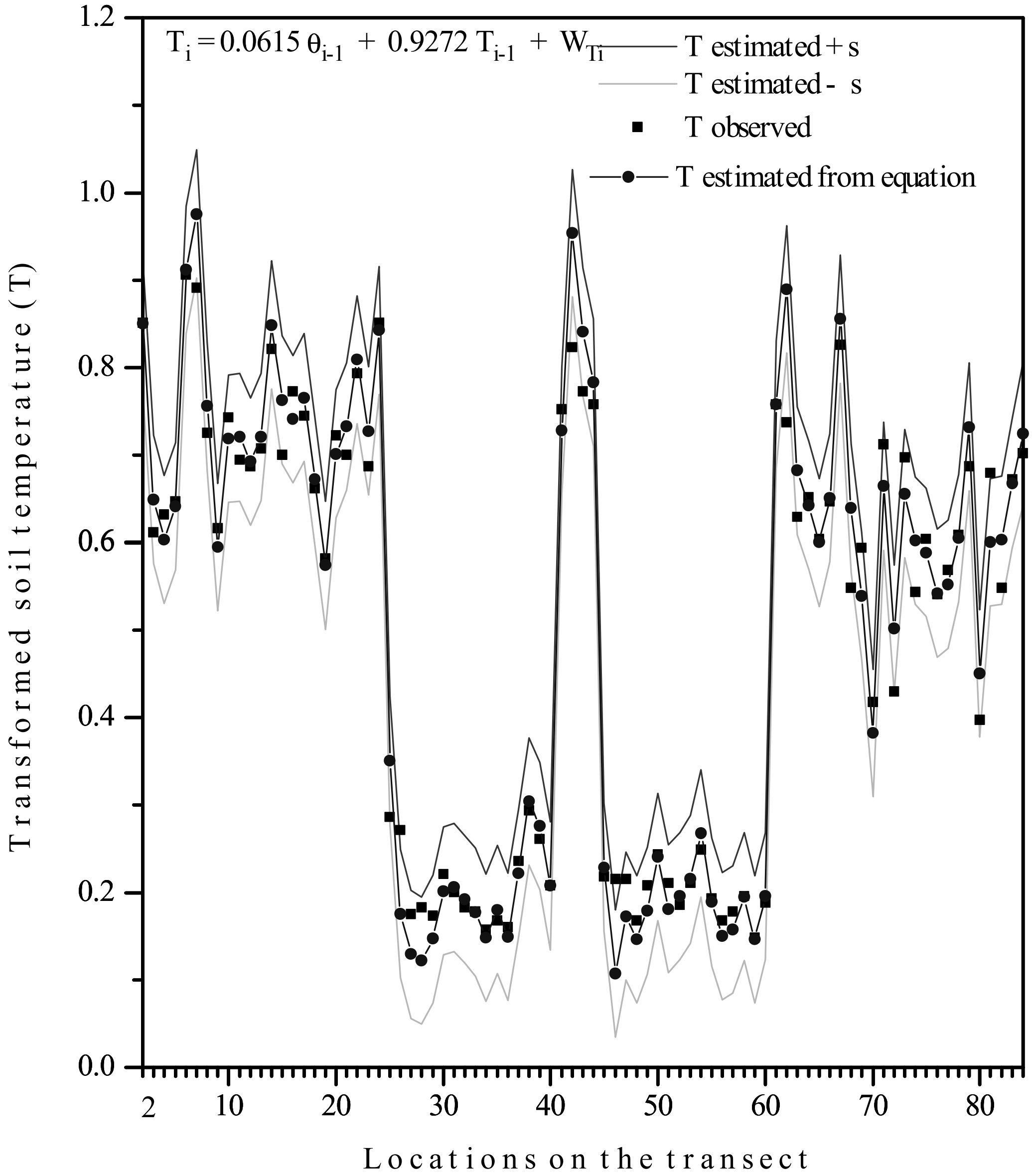

FIG. 5. State-space analysis of transformed soil-temperature data of Fig. 2, using the transformation: $x_i = [X_i - (m - 2s)]/4s$.

3.2. Soil water content and bulk density

Soil bulk density was monitored on rows 7, 8 and 9, along the 84-point transect, using a surface gamma-neutron gauge, Model CPN MC-3. It has to be pointed out that the experimental field was not machine harvested, and that the observed soil bulk density changes were due to foot traffic on interrows to make measurements and take instrument readings. The calibration of the surface gamma-neutron gauge in Ref. [4] presented an improvement in relation to the manufacturer's method. A new calibration equation was established for the probe shown in Fig. 7 using several materials, among them soils and sand, at various levels of moisture and density, pure tap water, and including results with the materials employed by the manufacturer. The density range for the used materials was 0.995 to 2.632 Mg m^{-3}. Figure 8 illustrates the changes of the calibration equation, when points of lower density were included. The lowest value used by the factory was 1.717 Mg m^{-3}, which, in some cases, is high for agronomic purposes. Figure 8 shows the calibration for the 0.05-m depth. A similar pattern was found for the other investigated depths.

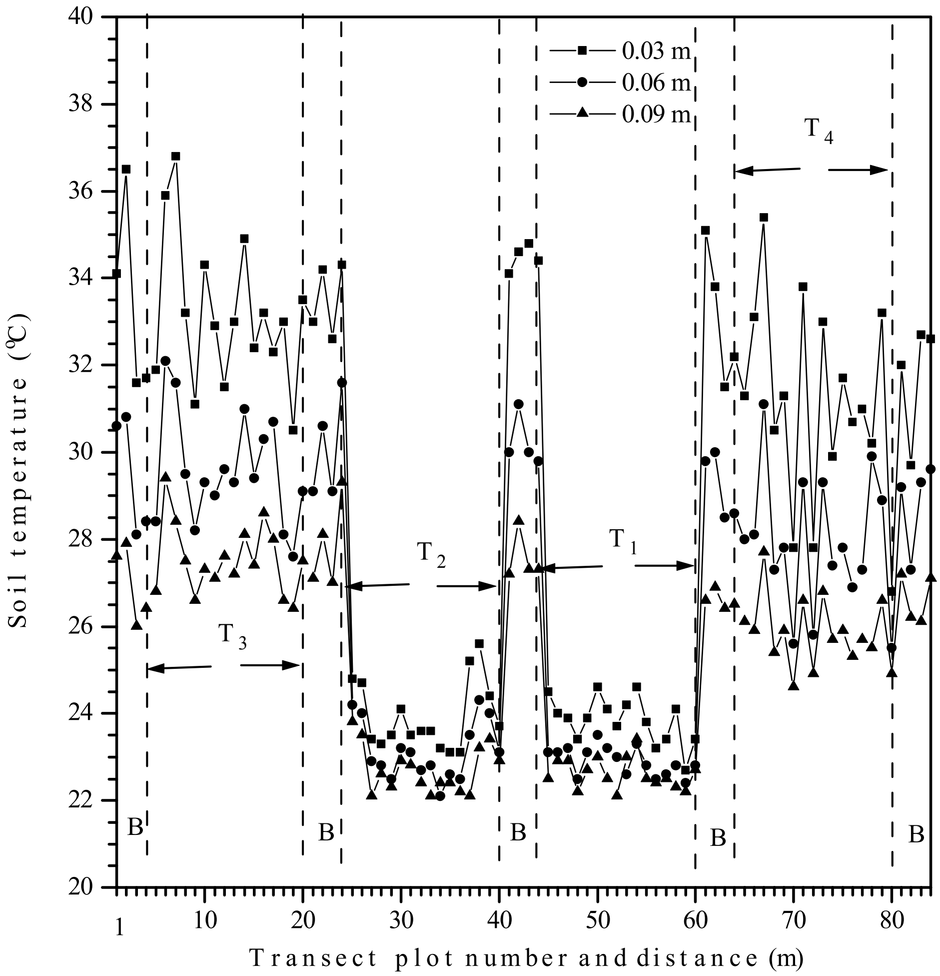

FIG. 6. Soil temperature transect for 18 November 1998. T1=mulched; T2=mulched; T3=bare; T4=burned residues; B=borders.

Table I. Average soil temperatures (four replicates, each with four sampling points) for the 0.03- to 0.09-m layer, at selected dates (T_1=mulched; T_2=mulched; T_3=bare; T_4=burned. Maximum, minimum, and mean air temperatures are also shown)

Date	Average soil temperature				Air temperature		
	T_1	T_2	T_3	T_4	Max	Min	Mean
	(°C)						
November 18, 1998	23.1c[a]	23.3c	30.1a	28.3b	32.8	19.7	26.3
December 2, 1998	23.1b	22.8b	29.8a	30.2a	35.0	18.0	26.5
December 18, 1998	23.9bc	23.8c	24.5a	24.4ab	27.6	20.8	24.2
January 12, 1999	23.1b	23.3b	23.8b	28.3a	29.8	20.0	24.9
February 5, 1999	23.8a	23.8a	23.5b	23.4b	33.7	19.8	26.8
March 4, 1999	22.7a	22.9a	22.7a	22.3b	32.0	18.4	25.2
April 7, 1999	22.3b	22.6a	22.6a	22.1c	32.2	18.4	25.3
May 14, 1999	17.4a	17.4a	17.7a	17.6a	22.5	9.0	15.6
June 29, 1999	15.5b	15.6b	16.3a	15.3b	27.8	14.2	21.0

[a]Averages within dates followed by the same letter do not differ significantly at the 5% level by Tukey.

Table II. Plant growth evaluation at harvest (October 1999) (averages of sixteen replicates per treatment)

Treatment	NS[a] (per m)	WS[b] ($kg\ m^{-1}$)
T_1	39.7b[c]	51.1b
T_2	40.3b	55.3ab
T_3	47.8a	63.2a
T_4	45.2ab	58.1ab

[a]Number of stalks. [b]Weight of stalks. [c]Averages in a column followed by the same letter do not differ at the significance level of 5% by Tukey.

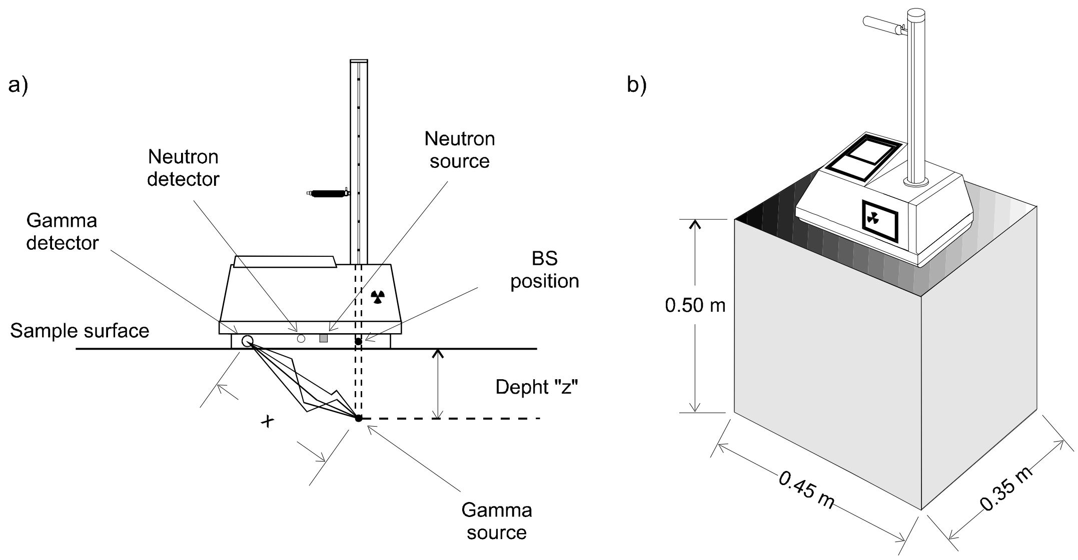

FIG. 7. Schematic diagram of the neutron probe: (a) measuring position, (b)with container for artificially packed samples.

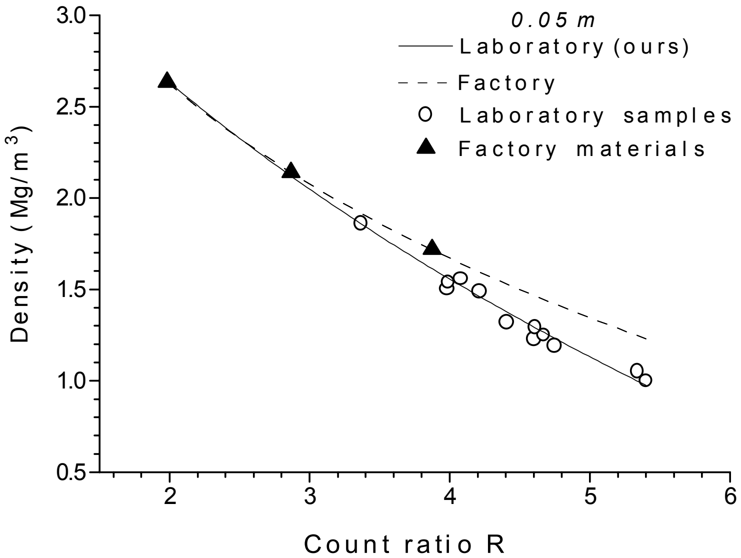

FIG. 8. Factory calibration as compared to our own laboratory calibration, for the 0.05-m position.

It can clearly be seen that the factory calibration, which was obtained from three high-density materials, coincides with our calibration curve only for a specific range of densities, more specifically for materials of high and intermediate densities. For low-density values, like those found in most soil profiles, for which the factory calibration should be extrapolated, it can be seen that deviations can reach values up to 16% higher, in relation to gravimetric measurements.

Along with the calibration efforts, an algorithm was developed [5] to explore soil layers. It was shown that using single-probe surface neutron-gamma gauges it is possible to detect compacted layers at depths in the range 0 to 0.30 m. The comparison between densities measured gravimetrically and with the aid of the gauge indicates that the density value obtained by the gauge represents a mixture of the densities crossed by the gamma-ray beam along its path. When compacted layers present a large difference of density in relation to the surrounding medium, it is possible to reproduce gravimetric data using gauge data and the proposed algorithm. The analysis showed that the probe yields less-exact and more-disperse values for shallow depths.

The relationship between soil-water content and bulk density is presented in [6]. Figure 9 shows the temporal evolution of soil-water contents, comparing the mulched-soil content θ_m with the bare-soil content θ_b. For all 300 days of measurements during the first ratoon crop cycle, the mulched rows presented 0.04 m^3 m^{-3} higher soil-water contents in relation to the bare rows, which corresponds to an increase of about 15%. A very good correlation was obtained between θ_m and θ_b:

$$\theta_m = 0.14 + 0.640\theta_b \quad (r=0.93;\ P<0.01) \tag{3}$$

and, in terms of average values, the following relation was found:

$$\bar{\theta}_m = 0.04 + \bar{\theta}_b \tag{4}$$

where

$\bar{\theta}_m$ and $\bar{\theta}_b$ are the time averages of θ for the mulched (T_1 and T_2) and bare (T_3) rows, respectively.

Similar behaviour was observed when comparing the mulched rows (T_1 and T_2) with the burned residuals (T_4), however in a lower intensity, showing only 0.01 $m^3.m^{-3}$ higher θ values in relation to T_4. The following relations were found:

$$\theta_m = -0.03 + 1.1\theta_b \quad (r=92;\ P<0.01) \tag{3a}$$

and

$$\bar{\theta}_m = 0.01 + \bar{\theta}_r \tag{4a}$$

where

θ_r is the soil water content of the burned residual rows, and

$\bar{\theta}_r$ is the time average.

Average dry bulk density data along the three rows are presented in Fig. 10 for two depths, 0.15 and 0.30 m. ANOVA was applied to all available data in order to verify differences among treatments. Table III shows the average D_b values for each treatment at depths of 0.15 and 0.30 m and for the three lines. Results indicate that the 0- to 0.30-m layer was denser than the 0- to 0.15-m layer for all treatments. For both depths, the bare-soil treatment (T_3) and the burned-residue treatment (T_4) presented higher densities in relation to those that were straw-mulched, T_1 and T_2, a fact that could be explained by the protective effect of the mulch on soil compaction.

It is concluded that the change of sugarcane management practice of burning trash in the field after harvest, to the practice of leaving trash as a mulch for the next ratoon crop, increased soil water content only slightly (about 4%) in the 0- to 0.15-m layer. In comparison to bare interrow, the increase in soil water content was significantly higher (about 15%). It was observed that, in terms of soil bulk density, the mulching of soil with harvest trash mitigates compaction.

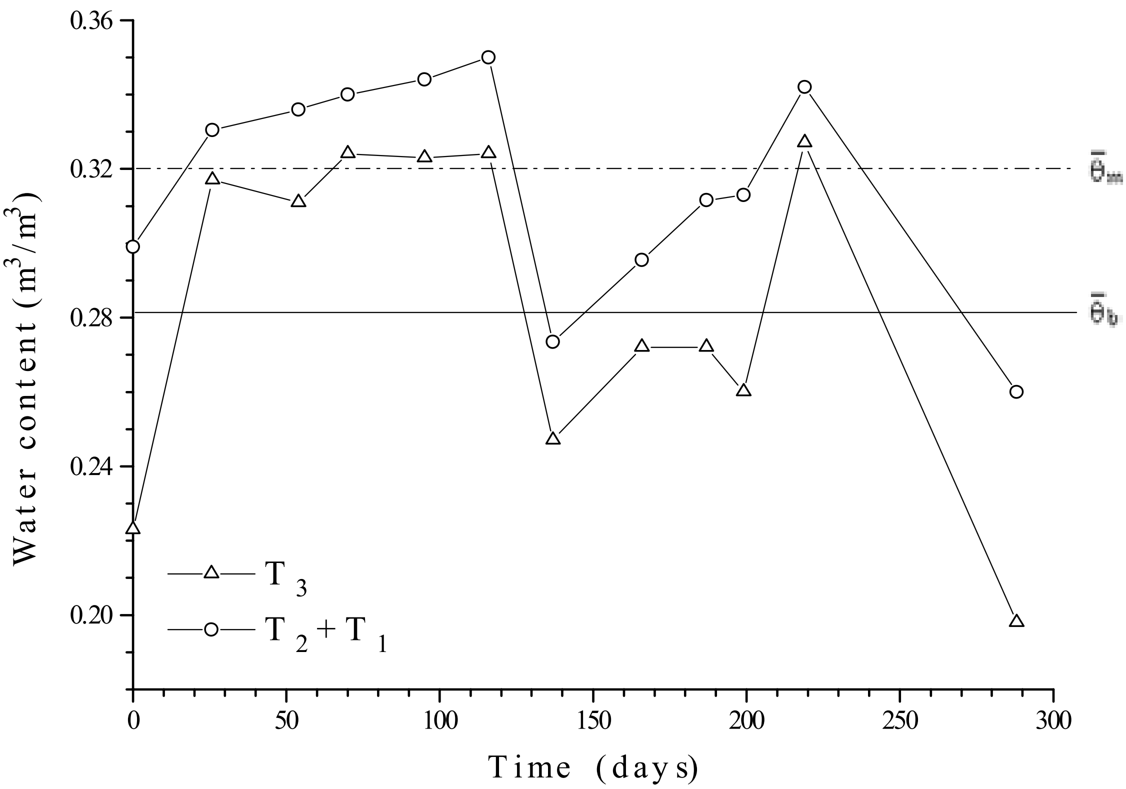

FIG. 9. Time evolution of average soil-water content, comparing mulched treatments (T_1 and T_2) with bare interrow (T_3).

Table III. Average soil dry bulk density as a function of depth, for the three rows of treatments T_1 and T_2 (straw mulch), T_3 (bare soil) and T_4 (burned residues), for three dates

Treatment	Dry bulk density	
	0.15 m	0.30 m
	(kg m^{-3})	
T_1	1,385d[a]	1,458d
T_2	1,415c	1,487c
T_3	1,470b	1,553b
T_4	1,512a	1,571a

[a]Means within a column followed by the same letter do not differ significantly at the 5% level.

3.3. Water balance

To follow the dynamics of the water, a water balance was carried out [7] using the 0- to 1.0-m soil layer as the volume element. Rainfall was measured at the site, evapotranspiration was estimated from atmospheric parameters, soil water fluxes at the 1.0-m depth were calculated from Darcy's equation, and run-off was measured by difference. Results did not reveal significant differences among treatments.

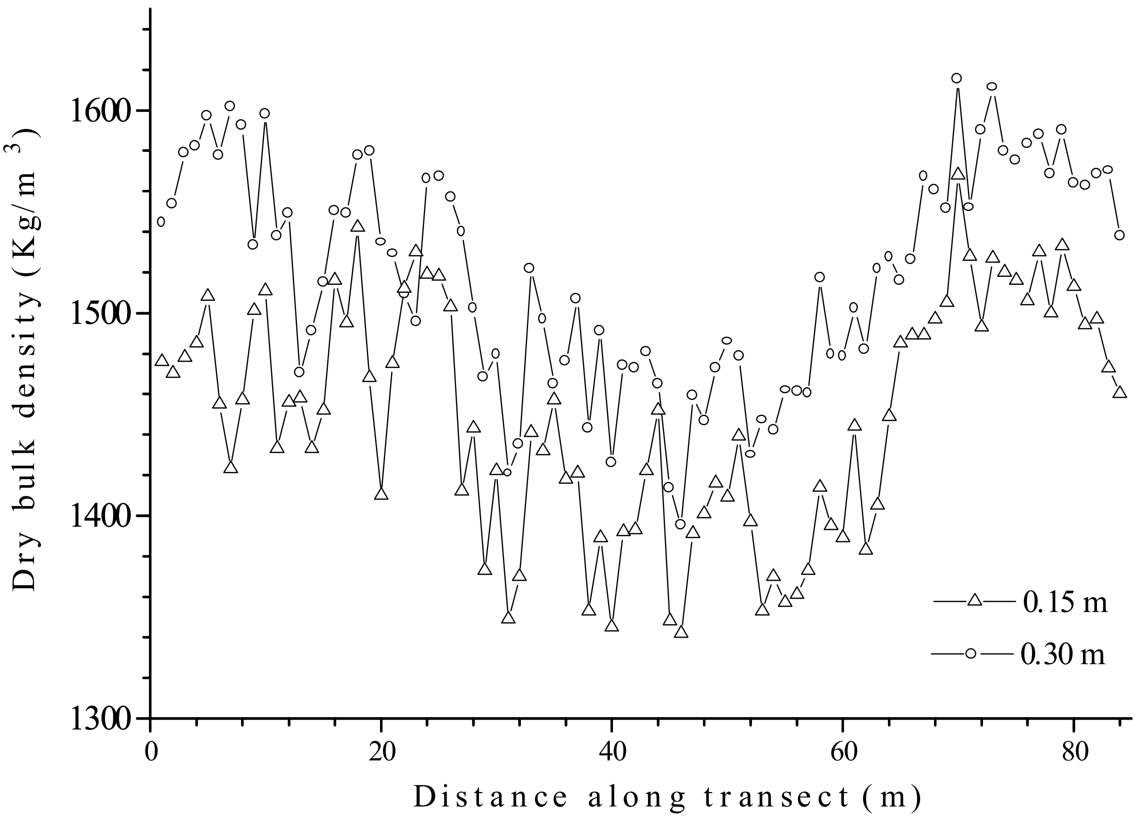

FIG. 10. Spatial variability of average (three lines) dry soil bulk densities, for two depths.

Table IV. Soil (Rhodic Kandindox) chemical characteristics (0–0.2 m layer) of the sugarcane field

Replicate	pH in $CaCl_2$	SOM ($g\ dm^{-3}$)	P ($mg\ dm^{-3}$)	K	Ca	Mg
				($mmol_c\ dm^{-3}$)		
T_1R_1	5.1	26.0	35.8	4.3	59.5	15.8
T_1R_4	5.0	22.3	26.5	3.1	62.0	15.8
T_1R_2	4.9	22.8	32.5	3.0	58.5	14.8
T_1R_3	5.0	23.0	51.8	3.2	73.0	15.8
T_4R_1	4.8	24.5	31.3	3.7	66.0	15.3
T_4R_2	4.7	25.5	22.8	3.6	65.0	15.0
T_4R_3	4.7	23.5	19.5	3.0	58.3	13.8
T_4R_4	4.7	23.0	20.8	2.8	63.5	15.3
Mean	4.9	23.8	30.1	3.3	63.2	15.2
SD	0.16	1.35	10.53	0.50	4.91	0.68
CV (%)	3.3	5.7	34.9	14.8	7.8	4.5

$\rho = 1.374\ g.cm^{-3}$.

3.4. Soil chemical characteristics

Some soil chemical characteristics of part of the transect (points 45 to 60), corresponding to the labelled treatments T_1 and T_4, of samples collected before planting (October 1997) are presented in Table IV (pH in $CaCl_2$, OM, P, K, Ca and Mg). The analysis of these data indicated that the chosen area is relatively isotropic for crop production. There were no significant differences between replicates.

3.5. Nitrogen and soil organic matter

3.5.1. Materials and methods

For each replicate, composite soil samples were taken at depths of 0 to 0.15, 0.15 to 0.30, and 0.30 to 0.50 m for determinationsof total N (TN), ^{15}N, and soil organic carbon (SOC). By means of successive dry and wet sievings, at 2,000, 200 and 50 µm, of air-dry soil samples (<2mm), the following soil fractions (SFs) were obtained: 1, light SF_1, floating in water (200–2,000 µm), with coarse crop residues; 2, heavy SF_2 (200–2,000 µm), mineral fraction related to sand particles; 3, SF_3 (50–200 µm), organo-mineral fraction with plant residues at different stages of decomposition associated with fine sand particles; 4, heavy SF_4 (0–50 µm), organo-mineral fraction with humidified plant materials associated with clay and silt-sized particles and clay (precipitated by centrifugation); 5, solution SF_5 (0–50 µm), organo-mineral fraction that remain suspended in water after centrifugation. Non-fractionated samples were also used for SOC determination, to check the efficiency of the fractionation procedure.

In plants, composite (twelve sub-samples) leaf 3^+ samples per replicate were collected in February, May, and October 1998 for ^{15}N analysis. At the last date (harvest time), crop yields were determined measuring the number of canes, weight of canes, and weight of straw and tips (trash). After drying at 65°C the fresh weights were transformed into dry-matter (DM) yield data. Total N and ^{15}N enrichment values were measured with a mass spectrometer (ANCA–SL, Europe Scientific, Crewe, UK).

Nitrogen derived from fertilizer (Ndff), for any compartment[1] in the system was calculated from:

$$Ndff = \frac{atom\ \%^{15}N\ excess\ of\ compartment}{atom\ \%^{15}N\ excess\ of\ fertilizer} \tag{5}$$

Total amounts of N in any compartment of the plant or soil of the system, derived from fertilizer or residue (TNdff, kg ha^{-1}), were calculated according to:

$$\mathrm{TNdff} = \mathrm{Ndff}\,.\,(\mathrm{DMyield\ of\ compartment}).(\mathrm{total\ \ N\ content\ of\ compartment}, \%)/100 \tag{6}$$

where DM is expressed in kg ha^{-1}.

Leached N was estimated measuring the concentration (C_N) of total N, and the enrichment in ^{15}N of the soil solution, using porous-cup extractors, one per replicate, installed at the depth of 1.0 m. The total amount of leached N, Q_N (kg ha^{-1}), was estimated as follows:

$$Q_N = \int_{ti}^{tf} q_W . C_N . dt \tag{7}$$

where

t is the time, and
q_w is the soil water flux density at z=1.0 m, estimated from Darcy´s equation.

[1]Compartment: plant [stalk, tip and straw]; soil [SF_1, SF_2, SF_3, SF_4, SF_5]; Losses and Nitrogen in Other Compartments [LNOC].

The hydraulic conductivity of the soil was measured at the field site [8]. With the ^{15}N enrichment of the soil solution, Q_N values were transformed into leached N derived from fertilizer, using Eqq. (5) and (6).

4. RESULTS AND DISCUSSION

Figure 11 shows the values of ^{15}N atom % excess, measured for leaf 3^+, for the part of the transect that received labelled fertilizer in October 1997, on 10 February 1998, 13 May 1998, and on 15 October 1998 (harvest time). These data indicate the rate of fertilizer N uptake during the first year of the sugarcane crop, and also the data variability. In terms of means, Fig. 12 shows the evolution of the ^{15}N label in leaf 3^+ for the 3 years 1997–1998, 1998–1999, and 1999–2000 for all treatments. For the first year the fertilizer-N uptake increased up to May, and, thereafter, the increasing uptake of soil N decreased ^{15}N enrichment in the leaves. For the subsequent years, the label became distributed in the various compartments, and decreased steadily, being still readily measurable in the third year (2000). Treatment T_2 received the labelled straw of T_1, with an enrichment of 11.7% a.e. ^{15}N, and therefore, the evolution of the label in leaf 3^+ of T_2 was a measure of the cane uptake of mineralized N coming from T_1 trash (straw and tips).

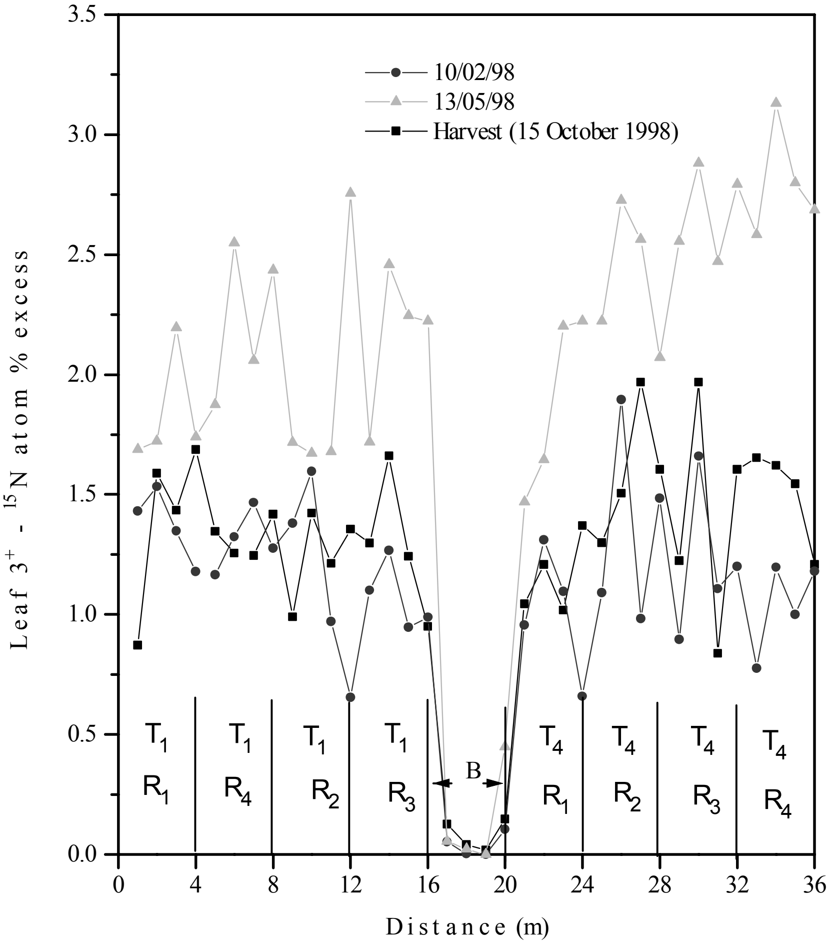

FIG. 11. Distribution of ^{15}N atom % excess in leaf 3^+ for three dates in 1998, covering the labelled part of the transect, which includes treatments T_1 and T_4.

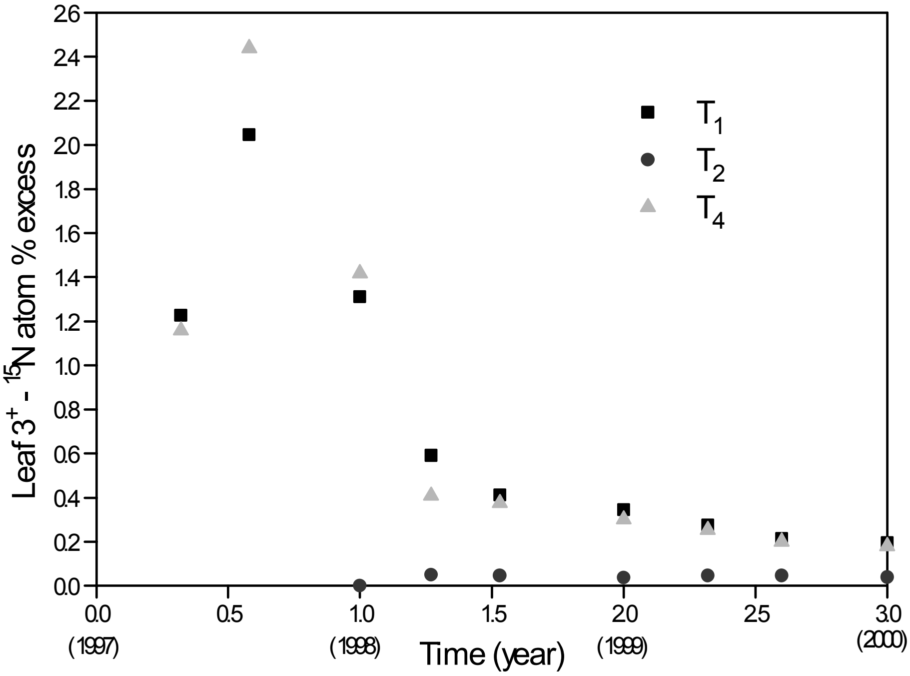

FIG. 12. Evolution of the ^{15}N label in leaf 3^+ samples for the period October 1997 to October 2000.

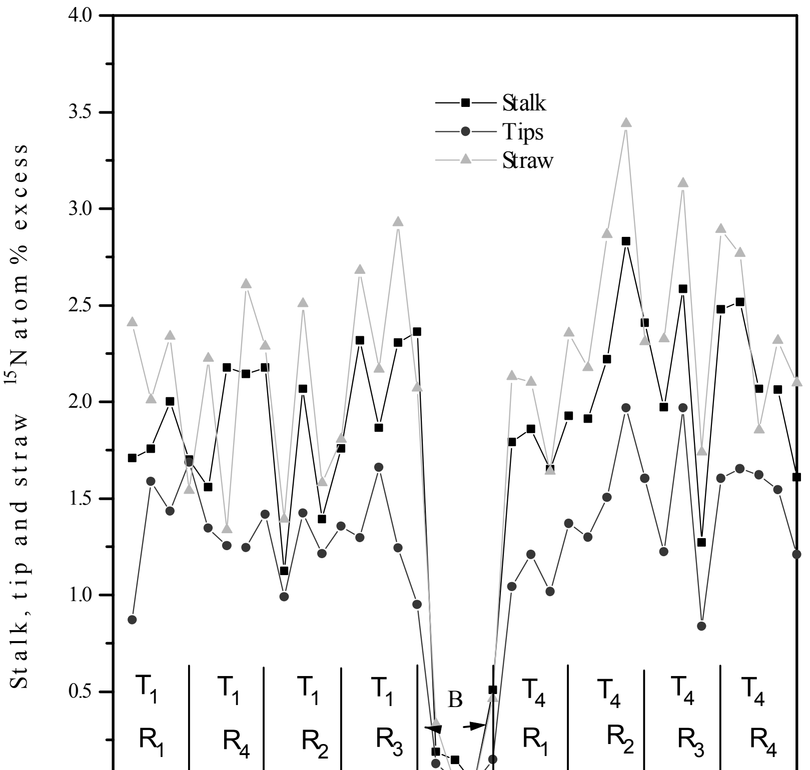

FIG. 13. Distribution of ^{15}N enrichment in stalk, tip (leaf 3^+) and straw at the October 1998 harvest.

Figure 13 gives an overview of the label distribution at the first harvest (October 1998), in the three chosen plant compartments (stalk, tip and straw) along the labelled part of the transect. Table V presents the overall N balance at the first harvest, taking into account soil and plant compartments. Soil fractionation data presented high coefficients of variation, mainly in the case of the mineral fraction SF_2, which was negligible in terms of amounts of total N. Plant-N variability was, in general, less than soil-N variability. It is important to note that the soil used in this experiment is very rich in N, presenting, on average, 7,667 kg ha^{-1}. Soil fertilization with N is, however, very important even at the relatively low rate of 63 kg N ha^{-1}, since it results in improved growth. Table VI presents the balance of the N derived from fertilizer (Ndff) at the first harvest (October 1998), showing the distribution of the ^{15}N-labelled fertilizer (63 kg ha^{-1}) applied at the beginning of the experiment (October 1997).

Table V. Distribution of total N content in all measured compartments, after 1 year, in October 1998

Compartment		T_1				T_4				Mean	SD	CV (%)
		R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4			
		(kg N ha^{-1})										
Soil	SF_1	89	40	88	65	74	52	79	63	68.8	17.2	25
(0–0.5 m)	SF_2	9	15	39	6	20	4	0	12	13.1	12.1	93
	SF_3	1,593	1,565	1,681	1,216	1,575	1,343	1,084	1,272	1,416	215.6	15
	SF_4	6,286	4,212	4,270	5,307	4,549	4,262	4,867	4,215	4,746	734	16
	SF_5	921	2,102	1,446	1,968	1,328	1,391	1,018	1,208	1,423	419	30
Soil total		8,898	7,934	7,524	8,562	7,546	7,052	7,048	6,770	7,667	755	9.8
Plant	Stalk	144	118	149	131	125	146	104	117	129	16.2	13
(Shoot)	Tip	79	77	75	80	77	74	73	69	75.4	3.5	4.7
	Straw	51	52	47	48	42	44	42	43	46.2	4.2	9.2
Plant total		274	247	271	259	244	264	219	229	251	20.0	8.0

Table VI. Distribution of the N derived from fertilizer in all measured compartments, after 1 year, October 1998

Compartment		T_1				T_4				Mean	SD	CV (%)
		R_1	R_2	R_3	R_4	R_1	R_2	R_3	R_4			
		(kg ha^{-1})										
Soil	SF_1	1.6	0.5	1.1	1.5	0.6	0.6	0.7	1.1	0.9	0.4	44
(0–0.50 m)	SF_2	0	0	0	0	0	0	0	0	0.0	0.0	0.0
	SF_3	1.7	1.3	1.5	1.3	1.2	1.1	0.9	1.4	1.3	0.2	19
	SF_4	5.0	3.4	4.0	4.8	3.5	3.4	3.6	4.2	4.0	0.6	16
	SF_5	0.6	1.7	1.3	1.5	0.7	1.0	0.5	0.9	1.0	0.4	41
Soil total (S)		8.9	6.9	7.9	9.1	6.0	6.0	5.7	7.6	7.2	1.3	18
Plant	Stalk	22.1	16.0	28.2	22.6	19.5	29.3	18.5	20.7	22.1	4.6	21
(Shoot)	Tip	9.4	8.2	8.2	9.0	7.6	10.0	8.8	8.9	8.8	0.8	8.6
	Straw	9.1	8.2	9.8	8.8	7.4	10.2	9	8.3	8.9	0.9	10
Plant total (P)		40.6	32.4	46.2	40.4	34.5	49.5	36.3	37.9	39.7	5.8	15
LNOC[a]		13.5	23.8	8.9	13.7	22.7	7.6	21.1	17.6	16.1	6.2	39

[a]Losses (denitrification, volatilization, leaching and erosion) and N in Other Compartments (0.5–1.0 m soil layer, rhizome, residual trash from last harvest, and other possible sinks), calculated as LNOC = F_N – (S + P).

To close the balance, Table VI provides the LNOC (Losses and Nitrogen in Other Compartments), which includes the losses (denitrification, volatilization, leaching and erosion), the 0.50- to 1.0-m soil layer, the rhizome, and the residual trash from the last harvest, which were not sampled.

Although not having sampled the rhizome completely, part of the N of the rhizome and of the root system are in the SF_1. This light organic fraction has, however, the least amount of ^{15}N, indicating that very little of the trash was incorporated by the soil at the 1998 harvest.

As expected, SF_2 did not present ^{15}N, since it is a mineral fraction constituted mostly of sand. The SF_3 and SF_5 fractions, the former related to sand particles and the latter to suspension, after centrifugation, presented similar amounts of ^{15}N, however about one third less than SF_4, related to clay and silt-sized particles precipitated by centrifugation. There are very few data in the literature, for tropical soils, that provide comparison with the soil-fraction data of Table VI.

Figure 14 presents the Ndff flow during the first 3 years of the experiment (1997–2000), for the mulched sugarcane treatments (T_1+T_2), showing N recovery. At this point, it is important to recall that at the harvest of 1998 the trash collected from T_1 and T_2 were interchanged, and that, in terms of amounts of Ndff or N recovery, the sum of both represents the mulched treatment.

Following the mass conservation principle, Fig. 14 presents the distribution of Ndff year after year, always summing up to the 63 kg ha^{-1} of labelled N applied to the crop in October 1997. "Exports" represent the Ndff of the stalks, used for sugar and alcohol production.

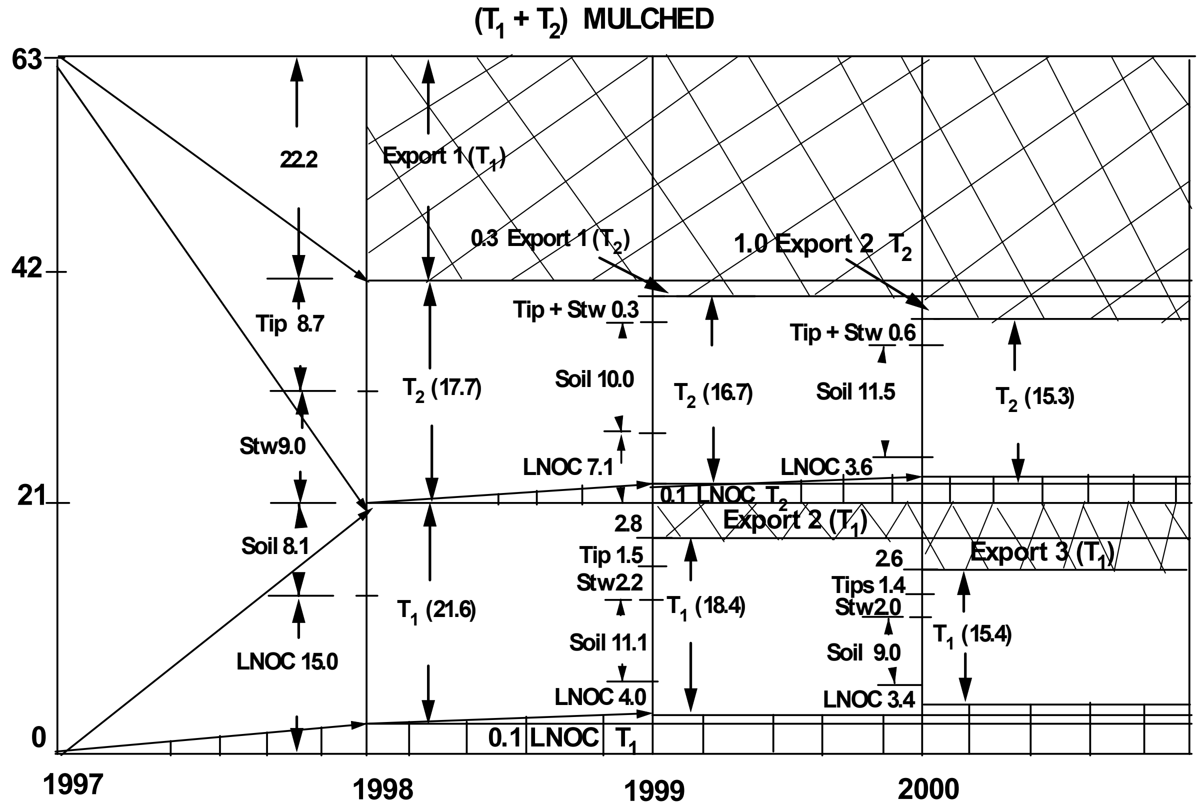

FIG. 14. Flow of N derived from fertilizer (Ndff) in different compartments for the mulched plots: T_1—^{15}N label in the soil; T_2—^{15}N label in trash.

As already defined, LNOC represents the amount of Ndff necessary to close the balance. Although the soil N content was 7.6 t ha^{-1} (Table V), it is mainly in immobile organic forms, since the amount of leached NO_3^- measured during the first year was very low, of the order of 1 kg N ha^{-1}, with negligible contribution of Ndff.

Other studies [9] carried out under similar conditions confirm the very low percentage of leached fertilizer. The 15.0 kg N ha^{-1} of the LNOC at the first harvest of 1998 consisted mostly of labelled N in the sugarcane rhizome, which was not quantified due to the crop's semi-perennial characteristics, thus retaining the labelled plots.

Ratoon sugarcane crops renew the rhizome yearly, the old one contributing to soil organic matter. Only a small part of the rhizome and root system N is included in the SF_1 fraction. As a result of rhizome renewal, the soil Ndff of T_1 increased from 1998 to 1999. Figure 14 also assumes that the lost part of LNOC Ndff was 10%. For T_2, the LNOC Ndff increased from 0 in 1998 to 7.1 kg ha^{-1} in 1999. Part of LNOC was the remainder of the labelled straw that came from T_1 in 1998, and the old rhizome, which absorbed part of the decomposed straw N. For treatment T_1, soil Ndff increased from 8.1 in 1998 to 11.1 in 1999. This increase could also be explained by rhizome decomposition.

Figure 15 is similar to 14, but presents data for the burned residues of treatment T_4, and it should be analyzed in a comparative way. Exports also represent Ndff of the stalks. During burning, the straw is completely carbonized and it is assumed that 100% is lost to the atmosphere. Tips having mainly green leaves are only partially burned. After harvest they are left on the ground, become drier due to insolation and, before sprouting of the ratoon crop, they are burned again. This second burning is not total, and partially burned tips are left on the ground. Therefore, the exported N in tips as a result of burning was assumed to be 50% (Fig. 15). Table VII presents details of the Ndff after 2 years, October 1999.

Table VII. Distribution of the N derived from fertilizer in all measured compartments, after 2 years, October 1999

Treatment		T_1					T_2					T_4				
Compartment		R_1	R_2	R_3	R_4	mean	R_1	R_2	R_3	R_4	mean	R_1	R_2	R_3	R_4	mean
Fertilizer (F_N)					21.6	21.6	17.7	17.7	17.7	17.7	17.7	26.2	26.2	26.2	26.2	26.2
								(kg N ha^{-1})								
Soil	SF_1	2.0	1.4	1.1	2.3	1.7	4.2	3.3	4.2	3.1	3.7	3.4	2.6	2.5	1.9	2.6
(0–0.5 m)	SF_2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	SF_3	2.6	2.5	2.0	2.9	2.5	1.3	2.2	1.4	2.6	1.9	3.3	3.8	4.0	2.3	3.4
	SF_4	6.0	5.3	6.2	4.5	5.5	3.1	3.2	2.7	3.3	3.1	7.7	9.4	8.7	6.7	8.1
	SF_5	1.7	1.8	1.0	1.2	1.4	0.7	2.0	1.8	0.9	1.4	2.7	1.8	1.8	1.3	1.9
Soil total (S)		12.3	11.0	10.3	10.9	11.1	9.3	10.7	10.1	9.9	10.1	17.1	17.6	17.0	12.2	16.0
Plant	Stalk	2.5	3.1	2.5	3.0	2.8	0.30	0.28	0.29	0.21	0.27	2.5	3.9	3.3	3.3	3.2
(Shoot)	Tip	1.4	1.6	1.6	1.6	1.5	0.16	0.19	0.13	0.10	0.14	1.3	1.3	0.95	1.3	1.2
	Straw	2.1	2.3	1.8	2.4	2.2	0.19	0.22	0.13	0.13	0.17	1.6	1.5	1.5	1.5	1.5
Plant total (P)		6.0	7.0	5.9	7.0	6.5	0.65	0.69	0.55	0.44	0.58	5.3	6.7	5.8	6.0	5.9
LNOC[a]		3.2	3.7	5.4	3.7	4.0	7.7	6.3	7.1	7.3	7.1	3.9	2.0	3.3	8.0	4.3

[a]Losses (denitrification, volatilization, leaching and erosion) and N in Other Compartments (0.5–1.0 m soil layer, rhizome, residual trash from last harvest, and other possible sinks). Calculated as LNOC = F_N – (S + P).

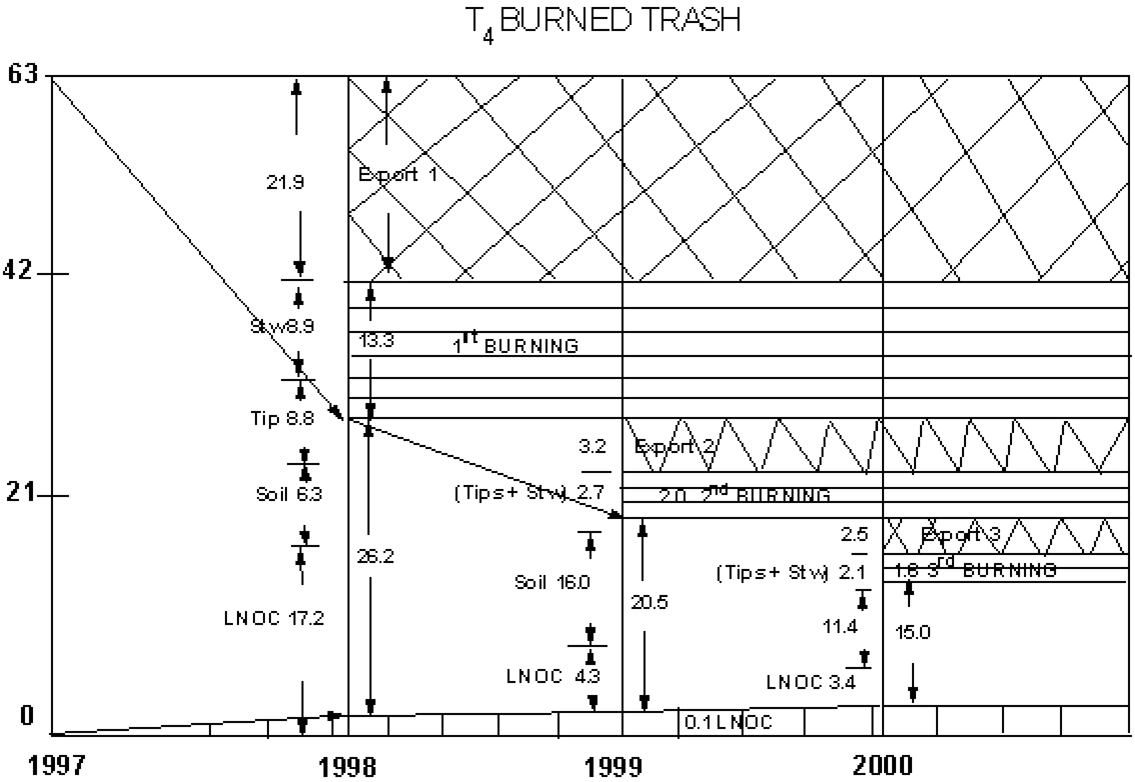

FIG. 15. Flow of N derived from fertilizer (Ndff) in different compartments for the burned trash treatment.

Table VIII. Evolution of exported and burned N derived from fertilizer for treatments T_1, T_2 and T_4, at harvests in 1998, 1999 and 2000

Harvest	T_1	T_2	(T_1+T_2)	T_4	Bur[a]	(T_4+Bur)
	(kg N ha^{-1})					
1998	22.2	0	22.2	21.9	13.3	35.2
1999	2.8	0.3	3.1	3.2	2.0	5.2
2000	2.6	1.0	3.6	2.5	1.6	4.1
			total: 28.9			total: 44.5

[a]Burned Ndff.

Table IX. Nitrogen derived from fertilizer available for sugarcane ratoon crops, immediately after harvests in 1998, 1999 and 2000,

Harvest	T_1	T_2	(T_1+T_2)	T_4
	(kg N ha^{-1})			
1998	21.6	17.7	39.9	26.2
1999	18.4	16.7	35.1	20.5
2000	15.4	15.3	30.7	15.0

Tables VIII and IX compare the traditional practice of trash burning before harvest (T_4) with the new management practice of leaving the trash on the soil surface as a mulch, in terms of N flow. During the 3 years of the experiment, the mulched plots had an export of Ndff equal to 28.9 kg ha^{-1}, whereas the burned plots lost 44.5 kg ha^{-1} of Ndff (export + burning), which was 53% more loss. As a consequence, the Ndff available for the ratoon crops was significantly higher for the mulched plots, as compared to the burned. However, this gain in Ndff did not affect sugarcane productivity, which was similar for non-burned (T_1+T_2) and burned T_4 treatments.

In relation to soil C, no significant differences were found between treatments since the period (2 years) of the study was too short. Yearly SOM measurements will be performed and it is expected that after 5 years differences between mulched and burned plots will be detected.

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COMPOSTING RICE STRAW IN SEMI-ARID CONDITIONS

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Abstract

Five experiments were conducted, three with 10-kg lots (in cement cylinders/digesters) and two in heaps with 500-kg lots of rice straw. Results from three—one with cement cylinders and two with heaps—are reported here. All were conducted at Patancheru from 1998 to 2000 in the hot summer period (April–May). The use of 0.76% N (as urea) with or without added micro-organisms more quickly decomposed the rice straw (by a subjective visual rating scale and C:N ratio) by about 1 week than otherwise. Also, the compost of N-applied treatments had at least 40% more N than that from the non-applied control. But N loss, indicated by the odour of ammonia, was noticed only from the N-applied treatments. All the treatments, except the control, received 25% rock phosphate (RP), when composting was done in cement digesters. For heap composting, RP was reduced to 6% so that its concentration would not be excessive when the compost is applied to crops at high rates. Composting was accomplished within 45 days whether in the digesters or in heaps, even with a reduced use of N (0.36% in 1999 and 0.1% in the year 2000). Treatment effects due to N that were apparent in the final product, disappeared when N-application was reduced to 0.3% or 0.1%. It was only through the visual rating that amendment with N and micro-organisms was perceived to shorting composting time. The resultant compost, however, did not indicate differences in chemical characteristics (N, P, K, OC%) across treatments in heap composting. One apparent biological difference across treatments was the presence of fruiting bodies of *Sclerotium rolfsii* (causes root rots in many crops) in control treatments. This fungus was not seen in treatments receiving microbial inoculation. In the experiment in 1999, we composted over 6 t of rice straw in a single session, in multiple heaps of 500 kg. The composting protocol is proposed for a small-scale village-level enterprise and is not intended for individual farmers.

1. INTRODUCTION

Crop residues are an important source of soil organic matter, which is low to very low in most soils in the tropics. Large quantities of the crop stubble [1] and crop residues are burnt in the arid, semi-arid and wet tropics [2]. Rice straw is one of the major crop residues that is burnt in the Philippines, Viet Nam, Sri Lanka, Pakistan and India. Although it is an important cattle feed in certain regions of these countries, in other parts it is available in excess of demand and is burnt. For example, about 12 Mt of rice straw and wheat straw are burnt annually in Punjab, India. Thus, N worth US $17 million is lost. In addition, burning causes environmental pollution (smoke) and the annual production of 28 Mt of CO_2, a greenhouse gas [2]. Similar data for other countries/regions are not available.

Rice straw may be disposed of by incorporation in soil where it decomposes naturally [3]. But the short time between harvest of rice and sowing of the next crop can result in incomplete decomposition and reduced yield from the subsequent crop. Long-term experiments (7 to 11 years) on incorporation of rice straw in the region have not been encouraging [3]. Furthermore, farmers need to use extra water for decomposition, and extra tillage for appropriate incorporation. Also, the machinery needed for incorporation is not readily available to many farmers, therefore they find burning to be a convenient means of residue disposal [2]. The straw can be applied as mulch [4,5], but research is needed to evaluate the feasibility of this practice in the intensively cropped regions of tropical and sub-tropical Asia.

Banger et al. [6] composted rice straw in 10-kg batches in cement cylinders. Rock phosphate and pyrite were added to enhance its value. Cuevas [7] developed a protocol for rapid composting of rice straw in large quantities for use by farmers in the Philippines. We modify it for use in the semi-arid climate of Patancheru. This paper describes the development of the modified protocol for composting rice straw.

2. MATERIALS AND METHODS

2.1. Composting protocols

2.1.1. In cement cylinders/digesters (1996–1998)

The experiment, repeated three times (once each year), had three treatments and a control: T1 = control (no amendment); T2 = rock phosphate (RP) at 25% on a dry-mass basis in relation to the rice straw; T3 = N + RP, i.e. N at 0.76% as urea, RP at 25%; T4 = inoculation with micro-organisms, i.e. the activator fungus *Aspergillus awamori*, the P-solubilizing bacterium *Pseudomonas striata* (strain 303), *Paecilomyces fusisporus* and *Bacillus polymyxa* (strain 411) for straw decomposition, and *Azotobacter chroococcum* (strain MAC 27) an asymbiotic N_2-fixing bacterium, and 0.76% N as urea and 25% RP.

Composting was done in cement digester tanks (75 cm diameter × 75 cm deep, with a lined base) buried in the soil and covered with galvanized iron lids. In each digester, 10 kg sun-dried rice straw (without chopping), moistened with a 15-L suspension of *A. awamori* and *B. polymyxa*, and 0.38% N as urea in water was placed as 10-cm-thick layers. Mats of *P. fusisporus* grown on potato dextrose agar plates, cut into 1-cm squares were placed randomly at every 10-cm depth in the digesters. Powdered Mussoorie rock phosphate (2.5 kg) was sprinkled between the layers. Eighty-two g of urea per digester were also added in the water used for soaking the rice straw. The surface of the rice straw in each cylinder was kept moist by sprinkling about 200 mL water at 2- to 3-day intervals. The contents of each digester were mixed at 20 days after starting the process. A second mixing was done at 30 days when 500-mL broths each of *A. chroococcum* and *P. striata* were sprayed onto the virtually composted straw. The final compost was analysed for traits such as pH, and inorganic nutrients using methods described by Jackson [8] and Page et al. [9].

2.1.1.1. Visual rating scale

Growth of fungi, strength of strands of rice straw and odour in heaps were used to assess composting: from 1 for least composted to 5 for most composted. Fungal growth was observed at at least ten spots per heap and at least once, between days 4 and 7, after setting up the composting. If fungal growth was seen at all spots, it was rated 5 and if growth was not visible or apparent at a few spots it was rated 1. The in-between ratings depended on the visibility of the fungal growth. Odour of the composting material was judged at the time of mixing the contents. Mature compost has a characteristic earthy smell, which was generally absent during composting. During composting the odour was like that of freshly wet straw or of fungi if it was progressing well. In some pockets, always associated with more than 80% moisture, generally at the base, hydrogen sulphide was detected and a rating of 1 assigned. This was associated with excessive watering. Dry pockets were obviously due to inadequate watering and did not compost. A well-composting heap was rated 4. Strength of the strands of rice straw was judged at days 30 and 45 or at termination of composting. If it was difficult to break a single strand of rice straw, as is the case with a fresh strand, it was rated 1. If it broke readily, it was rated 4 and if it broke and could be pressed like dough, it was rated 5. The intermediate ratings were subjective.

Mean ratings for a given digester or heap at the various times of observation, i.e. in the early stages, at mixing (day 30), and at maturity (day 45), were used to compare treatments. The composting rice straw changed from yellowish brown to dark grey. Application of rock phosphate disturbed the use of colour as a criterion for judging progress.

2.1.2. In heaps, phase I (1999)

The composting procedure was scaled up from 10-kg lots of rice straw to 500-kg heaps on the soil surface in a field. The experiment had three treatments including the control: i) control with no N, no P and no micro-organisms, with rice straw soaked in water; ii) bacterial inoculum with no N, no P and no fungi, with a previous batch of compost sprinkled into the moist rice straw as an inoculum, and, at the start of composting, rice straw was soaked in a water suspension containing an unidentified bacterium known to suppress the growth of several fungal species; iii) standard procedure with 0.3% N as urea, 6% Mussoorie rock phosphate (RP) and the activator fungus *A. awamori*.

The heaps were 5 m long × 1.5 m wide × 1.5 m deep, of 500 kg of sun-dried rice straw. Multiple heaps of this size allowed composting of large quantities of straw. The steps in the standard procedure (treatment iii) are described below. For the other treatments the relevant amendments were followed as described above.

A "soaking solution" was prepared in a large container: 150 L of water, 0.65 kg urea and 1 L of a blended suspension of *A. awamori* were mixed well. Sun-dried rice straw was weighed into convenient 5- to 10-kg bundles and dipped in the "soaking solution" for 2 to 3 min followed by draining for 5 to 10 min. The excess liquid was collected and reused. Each 10-kg bundle of straw absorbed some 15 L of soaking solution and, with it, 65 g urea, i.e. about 30 g N, i.e. 0.3% N on a dry-mass basis, and approximately 10^8 fungal propagules/spores. The moistened/inoculated straw aliquots was taken to a plastic sheet spread near the heaping point.

The inoculated/moistened straw was spread and sprinkled with the required amounts of RP, mixed well and placed in a heap. Each heap was covered with a plastic net (hole size 1- to 2-cm square) then with a 20- to 30-cm layer of non-experimental rice straw. Wetness of the fermenting straw at the centre, sides and top of representative heaps of each treatment was monitored manually. Water was applied such that the straw remained at 60 to 80% moisture all through fermentation. Contents of a given heap were mixed twice, at day 10 to 15 and at day 30. The experiment was terminated at day 45. At day 30, 500-mL suspensions of *Azotobacter, B. polymyxa,* and *P. striata*, grown separately and mixed at application, were sprayed per heap.

2.1.2.1. Watering

When sprinkled on top of a heap, water generally ran down the sides and did not penetrate to where it was needed. Therefore, a watering lance was used: a 1.5-m long piece of galvanized iron pipe welded to a 20-cm long tapering metal piece with a sharp end (containing four holes, 10-mm diameter, half way). When connected to a hose with water under pressure, jets of water issued from the lance, which, when plunged inside a heap at close intervals effected thorough wetting. Output of water from the lance was calculated per unit time, allowing application of close-to-correct volumes of water. For the dry season, a watering schedule was developed: about 100 L of water through the lance at day 7, mixing and watering the straw with water (about 240 L) at day 15, about 150 L at day 20, plus 200 L at day 30.

2.1.2.2. Internal temperature

A data-logger, model CR 21 (Campbell Scientific Inc., USA) was used. Copper-constantan (T-type) thermocouples were placed at five points in three representative heaps, one of each of the three treatments. Three of the five points were at the centre (base, middle, surface) of a heap and the other two were at the two sides (at the middle). The data-logger was programmed to record readings once every 2. Temperature were recorded continuously for the first 36 days.

2.1.3. Composting in heaps, phase II (2000)

This experiment had three treatments including the control, and three replications: i) control, i.e., no N, no P, no fungi and no bacteria; ii) standard procedure, as described previously, but with modifications over that of 1999; iii) no-N treatment, i.e. the same as the standard procedure but without N. Modifications in the standard procedure were as follows: urea was reduced from 0.3% to 0.1% and the rate of inoculation with the fungus was 1 mL suspension per L of water.

Also, the amendment bacteria (*Azotobacter, B. polymyxa,* and *P. striata*) were added, where appropriate, at the end of 45 days.

3. RESULTS

3.1. Composting of rice straw in cement digesters

The experiments in the first 2 years (1996 and 1997) were exploratory and the results were used to develop the protocols described in Materials and Methods. Data generated in 1998 are presented. Initially the pH was about 8. At day 30, pH of compost samples from the different treatments ranged from 7.0 in T4 to 7.5 in T1. As composting progressed, weight of the straw decreased due to loss of C. Weight-loss determinations were made weekly; Table I shows weight-loss data at day 30. Treatments T3 and T4 were visually most decomposed with the former losing more weight (56%) than the latter (50%). By 30 days, the control (T1) had lost only 46% weight, obviously due to less decomposition. The C:N ratios agreed well with the visual ratings; the most decomposed treatments, T3 and T4, had lower C:N ratios. The total N per digester was maximal in T4 (116 g) followed by that in T3 (101 g) and T2 and T1 (72 g). The total P in T2, T3 and T4, all of which received 25% RP, ranged from 177 g in T3 to 189 g in T4. Total K ranged from 133 g in T4 to 113 g in T2. Nitrogen and P were available only in small amounts in all cases. Phosphorus was negligible (0.02 g) in T2, which received 25% RP only, and ranged from 3.6 g in T1 to 5.3 g in T4. Available P ranged from 1.1 g in T1 to 3.1 g in T2. Available K was maximal in T4 at 112 g and minimal in T1 at 34.5 g.

3.2. Composting in heaps

Based on visual ratings, five of the six replicated heaps of the standard procedure were among the most completely composted. The mean rating was 3.3 (Table II). The heaps of the bacterial-inoculum treatment also composted well, with a mean score of 3.2. The control heaps composted most slowly and had a rating of 2.6.

The maximum weight loss at 30 days was 46%, recorded in the standard-procedure heaps (fungal inoculation, urea and RP) (Table II). The weight loss in the in the control heaps was close to that (45%). The heaps with bacterial inoculum registered minimum weight loss, although the progress in composting (indicated by visual ratings) was similar to that of the standard-procedure heaps The heaps receiving bacterial inoculum had low C:N ratios, indicating good decomposition.

There was an intense odour of ammonia around the standard-procedure heaps, indicating volatilization of N. However, there was no advantage in terms of shortening the number of days for composting over the bacterial treatment. Therefore, it seems possible that N application could be reduced (from 0.3%).

Table I. Composition of rice-straw compost at 30 days in cement digesters

Treatment	pH	H_2O (%)	Wt. loss (%)	Rating	OC (%)	C:N	Total per digester			Available per digester		
							N	P	K	N	P	K
							(g)					
T1, control	7.5	70	46	1	45	33	72	23	117	3.6	11	35
T2, 25% RP	7.5	61	45	2	29	29	72	179	113	0.02	3.1	92
T3, N+RP[a]	7.0	63	56	4	27	19	101	177	115	4.7	2.2	89.5
T4, inoculation[b]	7.0	62	50	4	29	19	116	189	133	5.3	2.6	112
SE (±)	0.2	1.8	5.6	—	1.2	1.4	7.6	14	6.2	1.8	0.14	6.5
CV (%)	5	5	19	—	7	8	15	17	9	90	10	14

[a]0.76% as urea, 25% RP. [b]Microorganisms, 0.76% N as urea, 25% RP.

Table II. Heap composting of rice straw, April–May 1999, at 30 days

Treatment	Rating	Weight loss (%)	C:N	$CaCl_2$-extractable P (ppm)
Control	2.6	45	11	72
Standard procedure	3.3	46	12	146
Bacterial inoculum	3.2	38	11	129
Mean	3.0	43	11	116
SE (±)	0.19	2.9	0.4	15
CV (%)	15	17	7.9	31

In all three treatments maximum temperatures were recorded at the centre of the heaps and minimum at the base (Fig. 1). Temperatures at the tops of the heaps fluctuated greatly. Overall, the highest mean temperature (for 36 days) was recorded at the centre of the heap of the control heaps (mean: 53.7°C, range: 25.5–63.2°C), followed by the standard-procedure (mean: 51.2°C, range: 24.6–68.2°C) and bacterial-inoculum heaps (mean: 47.0°C, range: 13.5–64.1°C).

Chemical analyses for N, P and organic C (OC) were done at 30 and 58 days. At 30 days, the bacterial compost had 33% more Kjeldahl N over the control and 15% more than the standard-procedure compost. Even N in the standard-procedure compost was significantly greater than in the control (Table III). However, these differences disappeared at 58 days and all three types of compost had 20.1 to 20.7 kg N t^{-1}. The total P was greatest when prepared with the standard procedure because it received 6% rock phosphate at the start of composting. Organic C measured by slow ignition in a muffle furnace was more in the bacterial and standard procedure composts than in the control. It was 29 to 30% greater in the bacterial compost and 13 to 34% greater in standard-procedure compost than in the control (Table III).

In the year 2000, the N concentration at composting was further reduced (from 0.3% N in 1999 to 0.1% N in 2000). Except for the N concentration, the standard procedure was the same in both years. The bacterial-inoculum treatment in 1999 was replaced by the fungus plus RP treatment in 2000. Composting in 2000 was terminated at 39 days. The total N values were similar in the two treatments at 12 kg t^{-1}, with the control having marginally higher at 14 kg t^{-1} (Table III). As in 1999, the total P was significant higher where RP had been added. Total K and OC were similar in all cases. Weight loss was significantly less in the standard procedure than in the control. The only apparent difference across treatments was the presence of fruiting bodies of the pathogenic fungus *Sclerotium rolfsii* (causes root rot in seedlings of several crops) in the control heaps in both years.

The compost prepared in 2000 was also analysed for four micronutrients. Concentrations of Zn and Cu were similar in compost of all three treatments (11.5 to 12.4 ppm and 0.5 to 0.7 ppm, respectively) (Table IV). Manganese was lowest at 85 ppm in the compost prepared following the standard procedure and highest at 112 ppm in the treatments receiving the fungal inoculum and RP, but the difference was not statistically significant. Iron was significantly higher (41.8 to 42.8 ppm) in composts receiving RP than in the control (11 ppm).

4. DISCUSSION

4.1. Composting of rice straw in cement digesters

In the initial studies we used 25% RP, then reduced it to 6% (on a straw dry-weight basis); with 7.0 to 7.4% total P, an application of 2 t ha^{-1}compost would provide 25 to 30 kg P. Although, less than 10% of the total P would be available, it is hoped that it would increase the P pool of the soil and become available in the long term through increases in populations of P-solubilizing micro-organisms added with the compost.

Table III. Nitrogen, P, K, and organic C per ton of rice-straw compost prepared in heaps (and weight loss at 45 days)

Treatment	Total N (kg)	Total P (kg)	Total K (kg)	OC (kg)	Weight loss (%)
1999, at 30 days					
Control	13.9	2.1	ND[a]	153	45
Standard procedure	16.1	9.8	ND	206	46
Bacterial inoculum	18.5	2.9	ND	200	38
Mean	16.2	4.9		186	43
SE (±)	0.79	0.20		8.8	2.9
CV (%)	12	10		12	17
At 58 days					
Control	20.4	2.9	ND	251	ND
Standard procedure	20.7	15	ND	284	ND
Bacterial inoculum	20.1	3.8	ND	325	ND
Mean	20.4	7.1		287	
SE (±)	0.26	0.17		1.99	
CV (%)	2	4		1	
2000, at 39 days					
Control	14.1	2.0	19.7	172	39
Standard procedure[b]	12.4	5.8	21.5	185	31
Fungus+RP	11.8	7.2	18.8	195	41
Mean	12.8	5.0	20.0	184	37
SE (±)	0.49	0.72	0.69	4.3	6.2
CV (%)	7	25	6	4	28

[a]Not determined. [b]Urea+fungus+RP.

Table IV. Micro-nutrient content of rice-straw compost prepared in heaps, 2000

Treatment	Mn (ppm)	Cu (ppm)	Fe (ppm)	Zn (ppm)
Control	105	0.5	11.0	12.4
Standard procedure	85	0.6	41.8	11.5
Fungus + RP	112	0.7	42.8	11.7
Mean	101	0.6	31.9	11.8
SE (±)	17.9	0.10	2.47	1.71
CV (%)	31	29	13	25

With addition of N, RP and micro-organisms (T4) it took about 40 days to decompose rice straw during the hot period, February to June during which the average monthly minimum temperature were 17 to 24°C and average maximum temperature were 29 to 39°C. Addition of micro-organisms did not influence rapidity of composting in this experiment, whereas in a previous experiment (one of the three experiments conducted in cement cylinders) the difference in the comparable treatments was at least 10 days. Amendment with RP without N and micro-organisms (T2) delayed decomposition by about 7 days as judged by the visual rating scale. The controls (T1) took about 60 days to decompose.

The advantage of using micro-organisms was not inconsistent from experiment to experiment. The difference in number of days for decomposition (at least of rating "4" on the "1" to "5" scale), with and without N, in three different experiments, one of which is reported here, ranged from nil to about 15 days, which was puzzling. Large differences in N content from batch to batch of rice straw (0.5% to 0.9%) seem to be the reason (0.6% N for the batch in Table I). Perhaps the micro-organisms are differentially affected according to N content, during composting.

4.2. Composting in heaps

Our previous experience suggested that maintaining 70% moisture inside the heaps was the most difficult part in the composting process. Adding water once a week and mixing was satisfactory, but labour intensive. It was manageable for 10-kg lots, but mixing 500-kg lots, was not practical. A watering lance (see Materials and Methods) proved very effective and obviated mixing the contents of compost heaps at weekly intervals. Only one mixing, at day 30, may be enough, but this needs further investigation.

Measuring temperature inside the heap and moisture content in straw were considered important to keep track of the progress of composting in heaps. Temperature differences across treatments suggested that different micro-organisms were involved in composting in the three treatments in 1999. Presence of fruiting bodies of the fungus *Sclerotium rolfsii*, which causes seedling death in many crops, was generally noted in control heaps, but not after microbial inoculation. This indicates the importance of inoculation.

A total of 6.6 t of rice straw was composted at one time. The process was aimed at a village-level enterprise. It was apparent that, even in large scale, composting can be accomplished in about 45 days. Even by 30 days the C:N ratio in all three treatments was similar (11 to 13). It should be possible to decompose any number of 500-kg lots. Further studies should address issues related to adaptability of the composting protocols at village level and its economics.

4.3. Other observations

Preparation of rice-straw compost involved use of RP and P-solubilizing micro-organisms. The RP had less than 4 mg kg^{-1} Olsen's P and rice-straw compost was assessed to have less than 8% Olsen's P (available-P; Table III), which may be due to these micro organisms and organic acids produced during composting. The micro-organisms used in the study have been developed through screening in laboratory cultures [10,11] where all growth requirements of the organisms are met. Under such conditions, less than 11 mg of the total 100 mg of P in the growth medium (which contained glucose and yeast extract) were dissolved by the six different bacteria and *Aspergillus awamori* in three weeks [11]. Thus, the micro-organisms were more efficient under the laboratory conditions than in the composting environment reported here. Also, the laboratory medium changed from pH 7 to pH <3 in three weeks. These micro-organisms were generally seven-times less effective [11] in solubilizing P in rock phosphate than in solubilizing P in tricalcium phosphate, which is also an insoluble form of P. There seems to be potential to identify P-solubilizing micro-organisms that are more efficient under composting conditions of high pH (>7) and poor nutritional content.

All available nutrients in compost are liable to leaching loss (in addition to their assimilation by micro-organisms) if a heap is not protected from excess watering or rain. About 0.2% of N, 6 to 23% P and 72 to 80% of K are susceptible. With high N addition (0.76%) at composting (see Table I) the loss of N could be 42 to 53%. Thus, addition of 0.1% N at composting, which resulted in less available N but completion of composting in about 42 days seems to have utility.

ACKNOWLEDGMENTS

We are grateful to Drs, K.K. Kapoor and Neeru Nirula, CCS Haryana Agricultural University, Hisar, India, and Dr. T. Singh, National Biofertilizer Development Centre, Gaziabad, Uttar Pradesh, India, for micro-organisms. Comments of Dr. C. Johansen and Dr. J. Dimes greatly helped to improve previous versions of the manuscript.

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RECYCLING OF CROP RESIDUES FOR SUSTAINABLE CROP PRODUCTION IN A WHEAT-PEANUT ROTATION SYSTEM

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Abstract

Field experiments were conducted in a sandy soil at west Samalout, Minia, Egypt, from December 1996 to October 1999. The main objectives were (i) to examine long-term effects of applications of crop residues on crop nutrition, yields and soil fertility; (ii) to improve process-level understanding of nutrient flows through the use of isotopic techniques, and (iii) to enhance the efficiency of use of nutrients by a wheat-peanut rotation system. There were four treatments: (i) T1, ^{15}N-labelled $(NH_4)_2SO_4$, 60 kg N/ha at 9.82% ^{15}N with unlabelled residues; (ii) T2, ^{15}N-labelled wheat residues, 26 kg N/ha at 1.94% ^{15}N a.e, applied at the end of the first season; (iii) T3, to generate unlabelled residues and yield; and (iv) T4, ^{15}N-labelled $(NH_4)_2SO_4$, 60 kg N/ha at 9.82% ^{15}N atom excess, applied at the beginning of the first season, without residues. The Ndff recoveries during the first season in treatments T1 and T4 were 27% and 26% respectively, while 25% of the ^{15}N remained in the soil for T1 and T4. Thus, the total amounts of ^{15}N accounted for (in plant and soil) were 51% for T1 and 50% for T4. After the second crop, the total ^{15}N recovery was 25% and 13% for T1 and T4, respectively. Application of the crop residues seemed to decrease N losses from the soil. Values for %N derived from labelled residues (%Ndfr) by wheat (T2) were 1.0% and 0.4% during seasons 3 and 5, respectively, while recoveries of %Ndfr by peanut from T2 treatments were 3.7, 4.1 and 0.3 during seasons 2, 4 and 6, respectively. In the following five seasons (peanut-wheat-peanut-wheat-peanut), total ^{15}N recoveries by plant and soil were 67, 54, 34, 25 and 16%, respectively.

1. INTRODUCTION

To meet future demand, the cultivated crop-production area must increase by 50% in the next 25 years, which will be possible only if soil and water resources and inputs are used more efficiently. Consequently, there is increasing interest in utilizing soils of low or marginal productivity for crop production. The total annual production of agricultural residues in Egypt has been as much as 24 Mt, equivalent to very large amounts of N, P and K. The application of crop residues to the soil not only enhances the content of organic matter and increases crop production, it also decreases need for chemical fertilizers and mitigates environmental concerns.

Understanding how crop residues decompose and how the resulting released nutrients are recycled or lost is important for the development of more-efficient residue- and fertilizer-management practices. Decomposition rate of, and nutrient release from, crop residues are influenced by a number of soil-environmental and crop-residue factors. Soil micro-organisms play a major role in crop-residue decomposition and on the subsequent fate of the nutrients so derived. The amount of N supplied to the crop from an organic input is dependent on the mineralization of plant-unavailable organic forms to plant-available inorganic forms of N: ammonium and nitrate. Mineralization is a complex process influenced by many environmental factors [1–3]. Studies using ^{15}N-labelled plant materials have been useful in estimating crop-N uptake from organic-N inputs [2–6].

Table I. Initial physical and chemical soil characteristics

Component	Depth (cm)		
	0–15	15–30	30–50
Coarse sand (%)	41	41	41
Fine sand (%)	46	45	45
Silt (%)	9.3	9.1	9.1
Clay (%)	4.1	4.8	4.9
Texture	sandy	sandy	sandy
Soil moisture (%)	6.5	6.9	7.1
Bulk density (g/cm^3)	1.68	1.62	1.65
pH	8.13	8.65	8.68
CEC (cmol(+)/kg)	4.0	4.0	3.8
EC (mS/cm)	0.65	0.85	0.90
Organic matter (%)	0.11	0.10	0.10
Total N (%)	0.014	0.013	0.013
Organic C (%)	0.064	0.058	0.058
C:N ratio	4.54	4.46	4.46
Available P (ppm)	4.0	3.0	1.0
Available K (ppm)	0.37	0.37	0.38
Available NH_4 (ppm)	8.9	4.6	2.8
Available NO_3 (ppm)	0.2	0.1	0.1
Biomass N (µg/g)	24	16	–
Biomass C (µg/g)	98	63	27

2. MATERIALS AND METHODS

The experiments were conducted in sandy a soil (newly reclaimed land in the Minia Governorate, Egypt) at the Experimental Farm of Minia University during the 1996–1997, 1997–1998 and 1998–1999 winter seasons (November–May) and the summer seasons (May–October) using a wheat-peanut rotation each year. Mean day and night temperatures were 22°C and 10°C in the winter, and 35°C and 20°C in the summer, respectively. Relative humidity was 60 and 50% during the winter and summer, respectively. Soil samples were collected from three depths (0–15, 15–30, and 30–50 cm). The collected samples were air-dried and crushed to pass through a 2-mm sieve. Physical and chemical characteristics are presented in Table I.

A randomized complete block design was used, with four treatments and four replicates. Individual plot size was 8×20 m (160 m^2) each with an ^{15}N-microplot of 4×4 m. The four treatments were: T1, ^{15}N-labelled $(NH_4)_2SO_4$, 60 kg N/ha at 9.82% ^{15}N with unlabelled residues; T2, ^{15}N-labelled wheat residues, 26 kg N/ha at 1.94% ^{15}N a.e, applied at the end of the first season; T3, to generate unlabelled residues and yield; and T4, ^{15}N-labelled $(NH_4)_2SO_4$, 60 kg N/ha at 9.82% ^{15}N a.e., applied at the beginning of the first season, without residues. Wheat (*Triticum aestivum* L.) var. Seds-1 and/or Beni Suef-6 and peanut (*Arachis hypogaea* L.) var. Giza-5 were used. For the first crop, wheat, microplots on T1 and T4 were amended with 60 kg N/ha [$(NH_4)_2SO_4$ enriched in ^{15}N at 9.82% atom excess, i.e. 5.89 kg ^{15}N/ha]. The ^{15}N fertilizer was split into four applications on T1 and T4 as follows: 25% at seeding, 25% at 2 weeks after seeding, 25% at 4 weeks after seeding and the last dose at 6 weeks after seeding. Plots of T1 and T4 also received 60 kg N/ha as unlabelled $(NH_4)_2SO_4$.

At the harvest, 1.5 kg of labelled wheat straw (1.94% a.e. with 1.14% N) from microplots of T1 were applied (5 kg/plot, equivalent to 3,125 kg/ha or 0.69 ^{15}N kg/ha) to the microplots of T2 after land preparation. Unlabelled wheat straw from T3 was applied at the same rate to the microplots of T1. Microplots of T4 had no addition of labelled or unlabelled wheat straw. In growing season 2, peanut seeds were inoculated before sowing with *Bradyrhizobium* grown on yeast-extract mannitol broth [7] for 6 days at 39°C, then grown with locally recommended cultural practices. At harvest, ^{15}N-labelled peanut residues from the microplots of T1 and T2 were removed and replaced with unlabelled peanut residues from T3. Nitrogen-15-labelled peanut residues from the microplots of T4 were removed without unlabelled peanut replacement. This sequence was repeated in seasons, 3, 4, 5, and 6 in the second and third years.

Superphosphate (15.5% P_2O_5) was applied to the wheat at a rate of 126 kg P/ha before sowing in all seasons. Potassium sulphate (48% K) was applied at a rate of 99.5 kg/ha. In other seasons, the same fertilizer regimen was applied, except that $(NH_4)_2SO_4$ was applied at a rate of 192 kg N/ha. With peanut, superphosphate was applied at a rate of 87.5 kg P/ha before sowing in all seasons. Ammonium sulphate was applied at a rate of 72 kg N/ha at 15 and 30 days after planting, whereas potassium sulphate was applied at 99.5 kg K/ha after 30 days.

Soil and plant samples were collected for every crop. Percentages of N derived from fertilizer (%Ndff), from residue (%Ndfr), and from soil (%Ndfs), were calculated according to the equations of Hauck and Bremner [8] and IAEA [9].

3. RESULTS AND DISCUSSION

3.1. Year 1, growing season 1, wheat

3.1.1. Yield

In the first year, growing season 1, only T1 and T2 had ^{15}N applied to their microplots. The yields from T1 and T4 ranged between 1,970 and 2,016 kg/ha for grain and 3,125 and 3,047 kg/ha for straw, respectively (Table II). Total yields were 5,095 and 5,063 kg/ha for T1 and T4, respectively. Differences were not significant.

Table II. Wheat yield, N and ^{15}N concentration and yield, Ndff and N-recovery (year 1, season 1)

Treatment	Plant part	Yield (kg/ha)	N (%)	^{15}N (%)	N yield (kg/ha)	^{15}N- recovery (g/ha)	Ndff (%)	N recovery (%)
T1	Grain	1,970	1.9	2.24	38.0	852	23	15
	Straw	3,125	1.1	1.94	35.6	691	20	12
	Total	5,095	1.5	2.09	75.4	1,576	21	27
T4	Grain	2,016	1.8	2.74	37.1	1,016	28	17
	Straw	3,047	1.0	1.57	31.1	488	16	8.3
	Total	5,063	1.4	2.16	69.9	1,509	22	26
$LSD_{5\%}$	Grain	387	0.34	1.02	9.14	10.4	8.7	
	Straw	788		1.29				
	Total	1,098	0.89		5.20	12.8	8.5	

3.1.2. Nitrogen concentration and N yield

The plant material was labelled at 2.24% ^{15}N for grain (1.9% N) in T1 and at 1.94% ^{15}N for straw (1.1% N) (Table II), and in treatment T4 2.74% ^{15}N and for grain (1.8% N) and 1.57% ^{15}N for straw (1.0% N).

There were no significant differences in terms of total N yield in grain and straw for T1 and T4. The concentration of N in the soil was very low at 0.01 to 0.03% (Table III) and tended to be higher in the surface layer (0–15 cm) than in the 15- to 30-cm layer. A concentration of 0.03% was equivalent to 608 kg N/ha. The concentration of ^{15}N in the surface layer was 1.84% for T1 and 1.68% for T4, whereas for the 15- to 30-cm layer values of 0.09% and 0.20% were recorded for T1 and T4, respectively.

3.1.3. Percent N derived from fertilizer

Values for %Ndff were determined for T1 to be 23 and 20 for grain and straw, respectively, and 28 and 16 for T4 (Table II). The differences were not significant.

In soil, the %Ndff values for the surface layer (0–15 cm) were similar for T1 and T4 at 1.9% and 1.7%, respectively, whereas, for the deeper layer (15–30 cm), the values were 0.95% and 0.21% for T1 and T4, respectively (Table III).

3.1.4. Nitrogen recovery

Percent recoveries of ^{15}N were higher in wheat grain than in straw both for T1 and for T4, with some differences between them (Table II). However, the total recoveries (g/ha) were similar. The percent of the N recoveries in T1 and T4 were 27% and 26%, respectively. As expected, there were no significant differences between treatments.

The ^{15}N recoveries (g/ha) in the topsoil (0–15 cm) were 2.5- to 3-fold higher than in the subsurface (15–30 cm) (Table III). The total recoveries, for 0- to 30-cm of soil plus plants were 52 and 50% for T1 and T4, respectively.

Table III. Soil N and ^{15}N concentration and yield, Ndff and N-recovery after harvest of wheat (year 1, season 1)

Treatment	Depth, (cm)	Soil wt. (t/ha)	N (%)	^{15}N (%)	Soil N (kg/ha)	^{15}N-recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)	Total N recovery plant+soil (%)
T1	0–15	2,025	0.03	1.8	608	1,118	1.9	19		
	15–30	2,100	0.02	0.09	420	391	0.95	6.6	25	52
T4	0–15	2,025	0.03	1.7	608	1021	1.7	17		
	15–30	2,100	0.01	0.20	210	426	0.21	7.2	24	50
$LSD_{5\%}$	0–15		0.01	0.2	11.2	13.3	0.20			
	15–30		0.01	0.03	6.40	5.70	0.04			

Table IV. Peanut yield, N and ^{15}N concentration and yield, Ndff and N-recovery (year 1, season 2)

Treatment	Plant part	Yield (kg/ha)	N (%)	^{15}N (%)	N yield (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)
T1	Leaves	2,828	1.1	0.242	31.1	75.3	2.5	1.3	
	Seeds	2,240	3.8	0.205	86.0	176	2.09	3.0	
	Hulls	1,100	0.71	0.200	7.81	15.6	2.04	0.03	4.3
T2	Leaves	2,859	1.7	0.024	48.0	11.5	1.2	1.7	
	Seeds	2,281	2.6	0.019	60.2	11.4	0.98	1.7	
	Hulls	1,127	0.87	0.024	9.81	2.35	1.24	0.34	3.7
T4	Leaves	2,937	1.2	0.251	35.3	88.5	2.6	1.5	
	Seeds	2,297	3.54	0.192	81.3	156	2.0	2.7	
	Hulls	1,162	0.60	0.195	6.97	13.6	2.0	0.23	4.4
$LSD_{5\%}$	Leaves	1,091	0.24	0.084	26.8	10.1			
	Seeds	769	0.66	0.086	44.4	19.7			
	Hulls	410	0.36	0.067	14.3	1.41			
	Total	708							

3.2. Year 1, growing season 2, peanut

3.2.1. Yield

The different plant parts of peanut (leaves, seeds and hulls) showed no significant differences among T1, T2, and T4 (Table IV). Higher values for T4 were not significantly greater, possibly due to the wide C:N ratio of wheat straw (43:1) and its slow decomposition, affecting nutrient availability for plant growth.

3.2.2. Nitrogen concentration and N yield

Nitrogen concentration (%) and yield (kg N/ha) were higher in peanut seeds than in leaves or hulls (Table IV); treatments T1 and T4 produced higher N concentrations and more uptake of N compared with T2. The $\%^{15}N$ values in the various plant parts showed significant differences among the three treatments.

The topsoil (0–15 cm) values for %N generally were higher than for the 15- to 30-cm layer (Table V). and were comparable to those recorded for T1 and T4 growing-season 1. Nitrogen yield in the surface layer was 608 kg/ha for T2 and 405 kg/ha for T1 and T4. The concentration of ^{15}N in the surface layers decreased in the order, T1>T4>T2. In the 15- to 30-cm layer, ^{15}N concentration was less than in the surface layer, with the same decreasing order.

3.2.3. Nitrogen derived from fertilizer

In most cases, there were significant differences in %Ndff for the plant parts among the treatments (Table IV). The values in leaves were higher than in seeds or hulls, and those for T1 and T4 were higher than those obtained with T2.

In soil, %Ndff was higher with T2 and than for T1 and T4 (Table V).

Table V. Soil N and ^{15}N concentration and yield, Ndff and N-recovery after peanut (year 1, season 2)

Treatment	Depth (cm)	Soil wt. (t/ha)	N	^{15}N	Soil N (kg/ha)	^{15}N recovery (g/ha)	Ndff	N recovery	Total N recovery	Total N recovery plant+soil
			(%)				(%)			
T1	0–15	2,025	0.02	0.154	405	624	1.6	11		
	15–30	2,100	0.02	0.140	420	588	1.4	10	21	25
T2	0–15	2,025	0.03	0.045	608	273	2.3	40		
	15–30	2,100	0.02	0.040	405	162	2.1	24	63	67
T4	0–15	2,025	0.02	0.104	405	421	1.1	7.2		
	15–30	2,100	0.01	0.080	105	84.0	0.82	1.4	8.6	13
$LSD_{5\%}$	0–15		NS	0.05	10.3	12.1	0.30			
	15–30		NS	0.01	2.40	6.4	0.06			

3.2.4. Nitrogen recovery

Recovery of ^{15}N was generally higher in seeds than in leaves or hulls (Table IV). Seeds of T2 plants contained 11.4 g/ha compared with 156 and 176 g/ha for T4 and T1, respectively. In treatment T2, the ^{15}N recovered was less because its ^{15}N came from labelled wheat residues for only one season from the T1 microplot. The total %N-recovery values were similar for all treatments at 4.30, 3.7 and 4.4% for T1, T2 and T4, respectively.

The recovery of ^{15}N in the soil-surface layer of T1 was 624 g/ha, decreasing to 588 g/ha at 15 to 30 cm (Table V). With T4, 421 and 84.0 g ^{15}N/ha were present in the two layers of soil, respectively. The T2 values were intermediate. Total N recovery was recorded at 63% for T2, versus 21 and 8.6% for T1 and T4, respectively. The total N recovery after peanut, i.e. in plants plus soil, was 13% for T4, half of the value (25%) obtained with T1.

3.3. Year 2, growing season 3, wheat

3.3.1. Yield

The highest yield of wheat, for grain and straw, was obtained with T1, followed by T2 and T4 (Table VI). This may have been due to the decomposition of the peanut leaves in T1 and T2; no residues were applied to T4.

3.3.2. Nitrogen concentration and N yield

Although the %N in wheat grain was much higher than in straw, the yield of N in straw was higher (Table VI). The values recorded with T1 were higher than with T2 or T4. The %^{15}N-derived data in both grain and straw revealed significant differences among the treatments. Less ^{15}N was recovered with T2 (straw+grain 6.88 g/ha) than with T4 (27.9 g/ha) or T1 (26.0 g/ha).

Nitrogen concentration at 0 to 15 cm and 15 to 30 cm in the soil with T1 and T2 were 0.03 and 0.02%, respectively, and 0.02 and 0.01% with T4, respectively. So, the N yields (kg/ha) were highest with T1 and T2 than with T4 (Table VII). Nitrogen-15 concentrations decreased in the order T1>T4>T2. The recover of ^{15}N with T1 was nearly twice that with T4 and three times that with T2 at both depths.

Table VI. Wheat yield, N and ^{15}N concentration and yield, Ndff and N-recovery (year 2, season 3)

Treatment	Plant part	Yield (kg/ha)	N (%)	^{15}N (%)	N yield (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)
T1	Grain	1,330	3.6	0.037	34.8	12.9	0.38	0.22	
	Straw	5,333	0.82	0.030	43.7	13.1	0.31	0.22	0.44
T2	Grain	1,072	2.8	0.009	30.2	2.72	0.46	0.39	
	Straw	5,180	0.67	0.012	34.7	4.16	0.62	0.60	0.99
T4	Grain	1,059	2.9	0.043	30.8	13.3	0.44	0.23	
	Straw	4967	0.98	0.030	48.7	14.6	0.31	0.25	0.48
$LSD_{5\%}$	Grain	471	0.66	0.020	8.65				
	Straw	323	0.25	0.010	13.6				

Table VII. Soil N and ^{15}N concentration and yield, Ndff and N-recovery after wheat (year 2, season 3)

Treatment	Depth (cm)	Soil wt. (t/ha)	N (%)	^{15}N (%)	Soil N (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)	Total N recovery plant+soil (%)
T1	0–15	2,025	0.03	0.110	608	668	1.1	11		
	15–30	2,100	0.02	0.092	420	386	0.94	6.3	18	18
T2	0–15	2,025	0.03	0.040	608	243	2.1	25		
	15–30	2,100	0.02	0.043	420	181	2.22	26	51	52
T4	0–15	2,025	0.02	0.098	405	397	1.0	6.7		
	15–30	2,100	0.01	0.084	210	167	0.86	3.0	9.7	10
$LSD_{5\%}$	0–15		NS	0.02	21.3	35.8				
	15–30		NS	0.01	16.7	20.1				

3.3.3. Nitrogen derived from fertilizer

The %Ndff in grain was higher than in straw for T1 and T4, but not for T2, which gave the highest %Ndff values for both plant parts (Table VI). Treatment T2 also gave the highest %Ndff values for both soil depths (Table VII). The total %Ndff was 4.3, 2.1 and 1.9 for T2, T1 and T4, respectively.

3.3.4. Nitrogen recovery

Percent N recovery in T2 was higher in straw than in grain (Table VI). Total %N recovery in grain and straw of wheat was 0.99% for T2, and half that for T1 and T4 (0.44 and 0.48%, respectively). The total % N recovery in the soil was also higher for T2 (Table VII). The total %N recovery, plant plus soil, was 52, 18 and 10% for T2, T1 and T4, respectively.

3.4. Year 2, growing season 4, peanut

3.4.1. Yield

After 2 years and four growing seasons, the highest yields of peanut leaves, seeds and hulls were obtained with T2 (Table VIII), possibly due to the release of nutrients from wheat straw (growing seasons 1 and 3) and peanut leaves (season 2) as a result of favourable effects on soil properties and plant growth. While the T4 gave high yield of leaves, T1 yielded more grain.

3.4.2. Nitrogen concentration and N yield

Percent N was higher in the seeds of peanut than in the leaves or hulls (Table VIII). The N yields (kg/ha) in different plant parts were not significantly different among the treatments, although higher values were obtained in T2. Percent ^{15}N was lower for T2, and T1 and T4 gave similar values; ^{15}N recoveries in peanut yield had a similar trend. Values for %N and yield (kg N/ha) were similar in the topsoil (0–15 cm) for all treatments (Table IX) as was obtained for wheat in growing season 3. More N was present in the 15- to 30-cm layer than in the topsoil for T2 and T4. The %^{15}N concentrations in the soil were still lower with T2 compared with other treatments. The ^{15}N-recovery values in the surface layer were 559, 152 and 292 g/ha for T1, T2 and T4, respectively. The values in the 15- to 30-cm layer were lower, but showed a similar trend.

3.4.3. Nitrogen derived from fertilizer

Values for %Ndff were similar for leaves and seeds, respectively, for T1 and T4 and greater than those for T2 (Table VIII). In the peanut hulls, %Ndff was much higher for T2 (8.8) than for T1 and T4 (1.2). The %Ndff values were higher in the topsoil than in the 15- to 30-cm layer for all treatments (Table IX). Nitrogen derived form fertilizer percent was higher in the surface layer for all treatments; it was decreased T2>T1>T4.

Table VIII. Peanut yield, N and ^{15}N concentration and yield, Ndff and N-recovery (year 2, season 4)

Treatment	Plant part	Yield (kg/ha)	N (%)	^{15}N (%)	N yield (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)
T1	Leaves	2,219	1.2	0.234	26.4	61.8	2.4	1.1	
	Seeds	1,004	4.0	0.216	40.6	87.6	2.2	1.5	
	Hulls	970	0.71	0.113	6.89	7.79	1.2	0.13	2.7
T2	Leaves	2,688	1.5	0.024	41.4	9.93	1.2	1.4	
	Seeds	1,046	3.8	0.019	39.6	7.53	0.98	1.1	
	Hulls	1,005	0.62	0.170	6.23	10.6	8.8	1.5	4.1
T4	Leaves	2488	1.2	0.236	29.6	69.9	2.4	1.2	
	Seeds	982	3.8	0.230	37.2	85.6	2.3	1.5	
	Hulls	943	0.70	0.122	6.60	8.05	1.2	0.14	2.8
$LSD_{5\%}$	Leaves	1,136	0.21	0.060	14.8	8.2			
	Seeds	199	0.38	0.170	7.15	3.5			
	Hulls	191	0.16	0.050	1.74	1.6			

3.4.4. Nitrogen recovery

The total %N recovery in peanut showed a high value for T2 (Table VIII). Percent N recoveries were greater in the topsoil than in the subsurface (Table IX). Treatment 2 recorded high values in the surface and subsurface layers (Table IX). The total %N recovery in the soil was 30, 12 and 7.1% for T2, T1 and T4, respectively. Total %N recovery for peanut plants plus soil showed a similar trend (Table IX).

3.5. Year 3, growing season 5, wheat

3.5.1. Yield

The grain yield of wheat with T1 was higher than for T2 and the converse was true in terms of straw yield (Table X). This may have been due to the high %N with T2 promoting vegetative growth.

Table IX. Soil N and ^{15}N concentration and yield, Ndff and N recovery after peanut (year 2, season 4)

Treatment	Depth (cm)	Soil w. (t/ha)	N (%)	^{15}N (%)	Soil N (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)	Total N recovery plant+soil (%)
T1	0–15	2,025	0.03	0.092	608	559	0.94	9.5		
	15–30	2,100	0.02	0.041	420	17	0.42	2.9	12	15
T2	0–15	2,025	0.03	0.025	608	152	1.3	22		
	15–30	2,100	0.03	0.009	630	56.7	0.46	8.2	30	34
T4	0–15	2,025	0.02	0.072	405	292	0.73	5.0		
	15–30	2,100	0.02	0.030	420	126	0.31	2.1	7.1	9.9
$LSD_{5\%}$	0–15		NS	0.010	20.8	9.7				
	15–30		NS	0.010	11.9	5.3				

Table X. Wheat yield, N and ^{15}N concentration and yield, Ndff and N-recovery (year 3, season 5)

Treatment	Plant part	Yield (kg/ha)	N (%)	^{15}N (%)	N yield (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)
T1	Grain	1,906	2.8	0.008	53.8	4.30	0.08	0.07	
	Straw	2,953	0.6	0.008	16.2	1.30	0.08	0.02	0.09
T2	Grain	1,578	3.2	0.003	50.3	1.51	0.16	0.22	
	Straw	4,016	0.86	0.003	34.5	1.04	0.16	0.15	0.37
T4	Grain	1,890	2.4	0.019	45.9	8.73	0.19	0.15	
	Straw	3,000	0.49	0.014	14.7	2.06	0.14	0.04	0.19
$LSD_{5\%}$	Grain	320	0.53	0.010	4.92				
	Straw	296	0.21	0.010	5.70				

3.5.2. Nitrogen concentration and N yield

The concentration of N in wheat grain was higher than in straw (Table X). The total %N in wheat was highest for T2 followed by T1 then T4. Total N yield followed the same trend. Percent ^{15}N was highest for T4 and lowest for T2. The ^{15}N recovery was also higher with T4 and lowest with T2. Total N yields were higher in the subsurface soil for T1 and T4 (Table XI). Percent ^{15}N values were higher for T1. The recovery of ^{15}N was also highest with T1 followed by T4 then T2.

3.5.3. Nitrogen derived from fertilizer

Values for %Ndff in wheat for T2 and T4 were approximately twice those for T1 for grain and straw (Table X). The %Ndff values in the topsoil were higher than in the subsurface layer. Treatment T2 had higher %Ndff values than did T1 or T4 (Table XI).

3.5.4. Nitrogen recovery

Treatment T2 showed a high %N recovery in grain and a low recovery in straw (Table X); T2 recorded more recovery than T1 or T4. The same trends were obtained with the total %N recovery. Nitrogen recovery in the surface layer of the soil was higher than in the subsurface layer (Table XI). Nitrogen recovery with T2 was twice that with T1 and about four times that with T4. The total N recoveries in plant plus soil showed a similar trend.

3.6. Year 3, growing season 6, peanut

3.6.1. Yield

The three treatments had different effects on peanut yield. The total yield for T2 was higher than for T1 and T4 (Table XII).

3.6.2. Nitrogen concentration and yield

The %N values in leaves, seeds and hulls were similar for T1 and T2 (Table XII). It is noteworthy that the %N in the leaves was twice that in the seed for T1 and T2, and about thrice for T4. These data contrast with those obtained in growing seasons 2 and 4. The total N yields were 111, 99.4 and 97.8 kg/ha for T1, T2 and T4 , respectively. The highest %^{15}N value was obtained with T1 and the lowest was with T2; the same trend was observed for ^{15}N recovery.

Table XI. Soil N and ^{15}N concentration and yield, Ndff and N recovery after wheat (year 3, season 5)

Treatment	Depth (cm)	Soil wt. (t/ha)	N (%)	^{15}N (%)	Soil N (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)	Total N recovery plant+soil (%)
T1	0–15	2,010	0.03	0.09	603	543	0.92	9.2		
	15–30	2,055	0.03	0.02	617	123	0.20	2.1	11	11
T2	0–15	2,010	0.03	0.021	603	127	1.1	18		
	15–30	2,055	0.03	0.007	617	43.2	0.36	6.3	24	25
T4	0–15	2,010	0.03	0.04	603	241	0.41	4.1		
	15–30	2,055	0.02	0.028	411	115	0.29	2.0	6.1	6.3
$LSD_{5\%}$	0–15		NS	0.02	16.9	10.4				
	15–30		NS	0.01	14.1	7.82				

The N yields in the surface layer of soil were higher than in the subsurface layer (Table XIII). The highest value was recorded with T2 followed by T1 then T4. Percent ^{15}N was higher in the soil surface layer with T1 and lowest with T2.The same trend was observed for ^{15}N recovery.

3.6.3. Nitrogen derived from fertilizer

The %Ndff in hulls was higher than in seeds or leaves for T1 and T2, whereas the converse was obtained with T4, which gave the highest values in leaves (Table XII). The %Ndff data for the soil were highest for T1 for both soil sample layers (Table XIII). The total values for %Ndff were 1.4, 0.88 and 0.89 for T1, T2 and T4, respectively.

Table XII. Peanut yield, N and ^{15}N concentration and yield, Ndff and N-recovery (year 3, season 6)

Treatment	Plant part	DM (kg/ha)	N (%)	^{15}N (%)	N yield (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)
T1	Leaves	1,019	4.3	0.024	43.7	10.5	0.24	0.18	
	Seeds	2,050	2.1	0.065	42.4	27.6	0.66	0.47	
	Hulls	708	1.9	0.071	13.3	9.45	0.72	0.16	0.81
T2	Leaves	1,000	4.5	0.0013	45.4	0.59	0.07	0.09	
	Seeds	2,197	2.4	0.0013	52.3	0.78	0.08	0.11	
	Hulls	850	1.6	0.0055	13.8	0.76	0.28	0.11	0.31
T4	Leaves	967	5.3	0.037	51.5	19.0	0.38	0.32	
	Seeds	2,003	1.9	0.019	38.1	7.23	0.19	0.12	
	Hulls	750	1.1	0.021	8.25	1.73	0.21	0.03	0.47
$LSD_{5\%}$	Leaves	520	0.35	0.02	6.24	0.95			
	Seeds	316	0.41	0.01	4.10	1.10			
	Hulls	149	0.20	0.03	2.36	0.82			

Table XIII. Soil N and ^{15}N concentration and yield, Ndff and N recovery after peanut (year 3, seas. 6)

Treatment	Depth (cm)	Soil wt. (t/ha)	N (%)	^{15}N (%)	Soil N (kg/ha)	^{15}N recovery (g/ha)	Ndff (%)	N recovery (%)	Total N recovery (%)	Total N recovery plant+soil (%)
T1	0–15	2,010	0.03	0.087	603	525	0.89	0.90		
	15–30	2,055	0.02	0.048	411	197	0.49	3.4	12	13
T2	0–15	2,010	0.035	0.014	704	98.5	0.72	14		
	15–30	2,055	0.02	0.003	411	12.3	0.16	1.8	16	16
T4	0–15	2,010	0.025	0.065	503	327	0.66	5.5		
	15–30	2,055	0.013	0.023	267	61.5	0.23	1.0	6.6	7.1
$LSD_{5\%}$	0–15		NS	0.09	14.9	9.40				
	15–30		NS	0.05	11.3	8.86				

3.6.4. Nitrogen recovery

Percent N recovery in seeds of T1 was higher than in leaves whereas the opposite was found for T4 (Table XII). Total %N recovery values were 0.81, 0.31 and 0.47 % for T1, T2 and T4, respectively). The total %N recovery in the soil was also higher for T2 compared with other treatments (Table XIII). The total %N recovery values for plant plus soil were 13, 16 and 7.1% for T1, T2 and T4, respectively.

3.7. Nitrogen recovery over 3 years of the wheat-peanut rotation

It is clear that the addition of residues from wheat and peanut benefited crop growth as a result of the organic matter and N content, especially for peanut, a legume. The addition of residues increased the efficiency of N recovery (Fig. 1). Nitrogen recovery was higher in the early seasons (Fig. 2); this was because the N contained in the legume residues was only partially available for uptake during the first growing season and because beneficial effects of these residues are due largely to improved fertility of the soil in the long term [10]. Several investigations have shown that the incorporation in soil of low-N residues improves N mineralization [11–13]. The results of our experiments are consistent with this trend. Residue management appears to be important for maintaining and improving soil structure. This result was also consistent with those of Wani and Shinde [14], who reported that the incorporation of wheat straw favoured the growth of groundnut and gave higher yields of wheat as a subsequent crop.

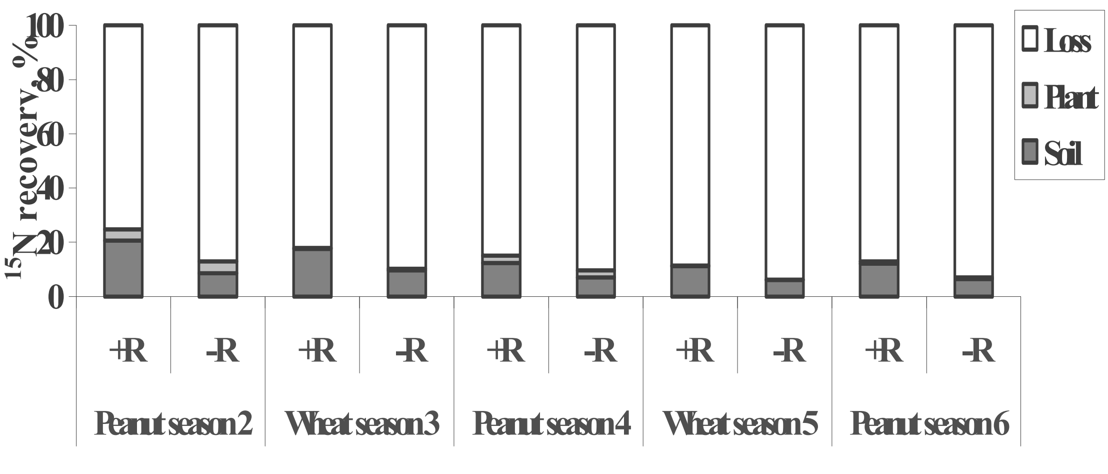

FIG. 1. Effect of incorporation of crop residues (+R=with residues; –R=without) on the recovery of mineral ^{15}N.

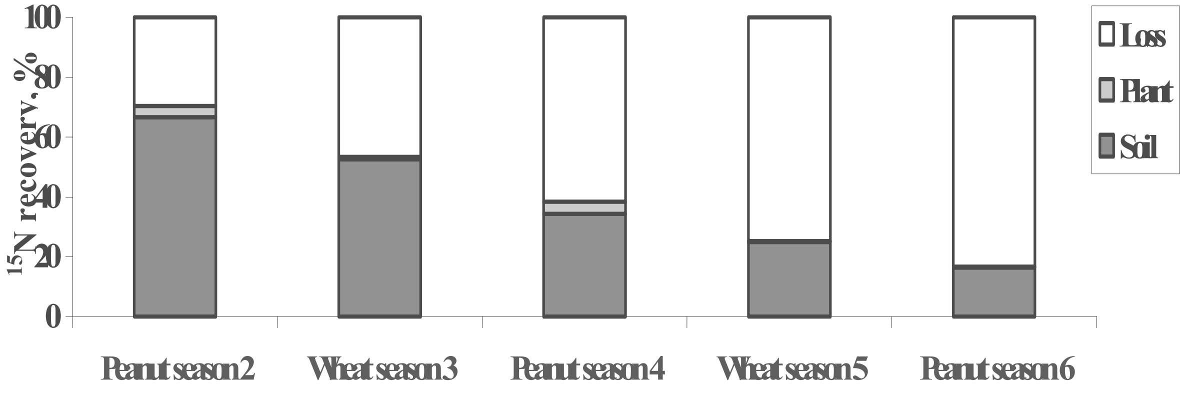

FIG. 2. Effect of incorporation of labelled crop residues on the recovery of ^{15}N.

4. CONCLUSION

In this sandy soil, deficient in organic matter (0.11%) and low in N (0.014%), wheat straw and peanut leaves (as residues) provided N for most of the growing period of the wheat-peanut rotation system. However, it appears that wheat straw and peanut leaves have little utility during the seasons of application. Incorporation of organic materials improved soil fertility and, hence, increased the yields of wheat and peanut.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the FAO/IAEA, Vienna, for support of the project on "The use of Isotope Technique in the Studies on the Management of Organic Matter and Nutrient Turnover for Increasing Sustainable Agricultural Production and Environmental Preservation" CRP/EGY 9033.

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IMPACT OF ORGANIC MATTER ON SELECTED SOIL PROPERTIES AND NITROGEN UPTAKE IN A CORN-MUNG BEAN CROPPING SYSTEM

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Abstract

The objective of the research was to determine the benefits of applying ^{15}N-labelled crop residue to a corn-mung bean cropping system. The first series of experiments, using two planting dates, revealed that organic matter enhanced soil physical and chemical parameters. Organic matter addition enhanced the availability of ^{15}N applied to the soil in previous seasons. Crop yields were increased by the supply of organic matter. A study of ^{15}N-labelled organic matter showed that N in crop residue was released in the surface layer of soil within 6 weeks of application. This was observed when the organic matter was applied two weeks before planting, at planting or two weeks after planting.

1. INTRODUCTION

The productivity of a tropical cropping system is influenced by interactions among many components, which collectively contribute to the success of the established crops. These components include soil type, climate, crop, organic matter, fertilizer, pests and diseases, management practice, and crop residues. All of these also have significant effects on soil organic matter, which determines soil productivity and sustainability. However, the effects of some parameters on soil organic matter are stronger than those of others [1,2].

Soil organic matter (SOM) holds large quantities of organically based plant nutrients, which, through mineralization, can become available for crop uptake or can be lost from the soil. Organic matter is also important for soil structure and reduces potential evaporation. It also influences pesticide retention and the CO_2 balance between the cropping system and atmosphere [3]. Thus, studies on SOM and its role in tropical cropping systems are of importance in maintaining economically and environmentally sustainable production programs.

Studies in the tropics have highlighted the importance of SOM in achieving sustainable cropping systems [4,5]. However, studies on upland rainfed systems have been few, although beneficial effects of green manure on corn production have been reported [6]. Hence, the FAO identified research on SOM as a priority for tropical dryland cropping systems [7].

Most studies on the use of organic matter for enhancing soil quality have been based on green-manure applications. In contrast, the use of crop residues, which generally are lower in nutrient content, has not been extensively reported in the developing world. Hence, a long-term program was initiated to evaluate the use of crop residues, readily available in tropical countries, that generally are of a high C:N ratio. The objective of the program was to ascertain the potential of using residues to release nutrients and maintain productivity of subsequent crops. The study concentrated on:

— The ability of ^{15}N-labelled corn-crop residue to release N to sustain productivity of a corn and mung bean rotation over six seasons in 3 years and to improve selected soil properties.
— Sequential release of N applied in the form of residues of corn at different times in relation to crop growth.

2. MATERIALS AND METHODS

The program of research consisted of two experiments based on a corn (*Zea mays* L.)-mung bean [*Vigna radiata* (L.) R. Wilczec] rotation carried out at the experimental station of the University of

Peradeniya, located at Dodangolla, Kundasala (7° N, 81° E, 421 m above sea level) in the mid-country intermediate zone of Sri Lanka.

The mean annual rainfall is 2,100 mm, of which 60 to 70% occurs from late October to late January [8]. The mean monthly temperature varies between 28 and 31°C, with a relative humidity of 60 to 70%. The mean daylength is 11 to 12 h

The soil is an Ultisol (Rhododult) with a clay-loam texture. The pH (1:2.5 H_2O) was 6.4, and the CEC was 4.2 mEq/100 g soil. The soil is low in organic C (0.83%), had 0.14 mg N per 100 g, 61 ppm available P and an exchangeable K content of 0.32 mEq/100 g.

2.1. Experiment 1

This experiment had two planting dates, namely in April 1997 and in September 1997, to correspond to the dry and wet seasons, respectively. The same treatments were applied on two adjacent sites.

Corn var. Bhadra was labelled with ^{15}N-enriched (10%) NH_4SO_4 followed by mung bean var. MI5. The experiment had a randomized block design with four replicates. Individual plot size was 8×6m, and each labelled microplot was 3×3m. Each yield area was 2×2m.

The treatments were as follows:

— Treatment 1, addition of labelled N fertilizer to the microplot, which received corn residues after harvest of above-ground biomass at crop maturity. In the second and subsequent seasons, the microplot received unlabelled mung-bean or corn-crop residues from treatment 3.

— Treatment 2, addition of labelled crop residue from Treatment 1 after harvest, to a microplot of the same size as in Treatment 1. In the second and subsequent seasons, the microplots received unlabelled mung-bean or corn residues from Treatment 3.

— Treatment 3, labelled fertilizer was not added.

— Treatment 4, labelled fertilizer added to the microplot and the residues were removed after crop maturity for all planting dates.

The fertilizer regimes used were as locally recommended [9]: corn was fertilized with the equivalent (/ha) of 60 kg N, 75 kg P and 75 kg K, and mung bean was supplied with the equivalent (/ha) of 40 kg N, 50 kg P and 60 kg K.

The spacings were 60×30 cm for corn and 30×8 cm for mung. The densities thus obtained were equivalent to 60,000/ha for corn and 400,000/ha for of mung bean. The dates of planting of the two sites were as follows:

Experiment 1A	First season, corn	05 April, 1997
	Second season, mung bean	27 September, 1997
	Third season, corn	03 May, 1998
	Fourth season, mung bean	18 October, 1998
	Fifth season, corn	10 May, 1999
	Sixth season, mung bean	15 October, 1999
Experiment 1B	First season, corn	25 September, 1997
	Second season, mung bean	05 May, 1998
	Third season, corn	14 October, 1998
	Fourth season, mung bean	20 May, 1999
	Fifth season, corn	19 September, 1999

All crops were planted on well tilled, weeded plots at the onset of rains in the respective seasons. The plots were weeded at regular intervals; weeds on the microplots were collected and dried for ^{15}N analysis to determine N from fertilizer or residues that was lost to the growing crops. The weeds removed during the cropping season were not incorporated into the plots, per farmer practice. However, at land preparation, weeds were incorporated after sampling. Irrigation was not provided.

After harvesting the crops, the organic matter was added in the form of crop residue in the following manner. The mean weight of the quantity of unlabelled corn residue added to Treatment 1 from Treatment 3 was 13.1±0.25 kg. The quantity of labelled residue added from Treatment 1 to Treatment 2 was 12.6±0.56 kg. These rates were equivalent to approximately 14 Mt/ha. The mean moisture content of corn residue was 49±2.1%. The mean weights of unlabelled mung bean residue added to Treatments 1 and 2 from Treatment 3 were 4.1±0.20 kg, equivalent to 4.5 Mt/ha. The moisture content of the mung bean residue was 57±2.9%.

In Experiment 1B, the mean weights of unlabelled corn residue taken from Treatment 2 and added to Treatment 1 was 13.3±0.31 kg. The labelled residue of corn moved from Treatment 1 to Treatment 2 was 13.1± 0.19 kg. The moisture content of the residue was 61±1.25%. On this basis, the rate of residue added was equivalent to 14.9 Mt/ha.

The mean weights of the quantity of unlabelled mung bean added from Treatment 3 to Treatments 1 and 2 in the second season were equivalent to those of Experiment 1A. The rates used in the third season were similar to those added at the end of the first season. The measurements made were as follows:

Corn and mung bean	Seed yield and the weight of residues ^{15}N enrichment of seeds and residue

Soils (determined at the beginning and end of each season)

	Bulk density Water-holding capacity Cation-exchange capacity Organic matter content

2.2 Experiment 2

This experiment, which monitored the release of enriched N from labelled organic matter, was carried out in the field adjacent to the Experiment 1, beginning in September 1998. Thus, the climate and soil of the site were similar to those for Experiment 1.

Tubes of PVC, 20 cm diameter and 50 cm long, were buried vertically in the soil, sixteen tubes per treatment which served as replicates. At each sampling, one tube per treatment per replicate was removed. As treatments, ^{15}N-labelled corn residues, at a rate equivalent of 14 Mt/ha (as used in Experiment 1), were added per tube at the following times:

— at harvest of the corn in Experiment 1A in September, 1998,
— two weeks before the planting of mung bean in Experiment 1A,
— at the time of planting of mung bean in Experiment 1,
— two weeks after planting of mung bean in Experiment 1A.

The tubes were kept weed-free at all times. Irrigation was not provided.

The soil of one tube per treatment per replicate was removed at 3-week intervals on four occasions and analysed for N content and ^{15}N excess at depths of 0 to 15, 15 to 30, and 30 to 50 cm. Soil-moisture contents were determined gravimetrically for each depth.

2.3. Nitrogen-15 analysis

The N contents and ^{15}N enrichment of samples of seed, residue, weed and soil from Experiments 1A and B and the N and ^{15}N contents of the soils of Experiment 2 were determined at the IAEA Soils Laboratory, Seibersdorf, Austria.

2.4. Data analysis

Analyses of variance were carried out on the data to determine the significance of observed differences between treatments.

The formulae used were as follows:

$$\%NdfF = \left[\frac{atom\ \%^{15}N\ excess\ in\ the\ crop}{atom\ \%\ ^{15}N\ excess\ in\ the\ fertilizer\ added}\right] \times 100$$

$$NdfF\ (kg) = \frac{\%NdfF}{100} \times [N\ in\ the\ crop]$$

$$\%N\ recovery = \left[\frac{NdfF\ (kg)}{amount\ of\ N\ applied\ as\ fertilizer}\right] \times 100$$

$$\%N\ derived\ from\ residue\ (NNdfR) = \left[\frac{atom\ \%^{15}N\ in\ crop}{atom\ \%^{15}N\ in\ residue\ added}\right] \times 100$$

$$\%NdfR\ (kg/ha) = \left[\frac{atom\ \%^{15}N\ excess\ in\ crop}{atom\ \%^{15}N\ excess\ in\ residue}\right] \times [N\ in\ crop\ (kg/ha)]$$

Table I. Bulk density and water-holding capacity of soil as affected by addition or removal of organic matter (Experiment 1A)

Treatment	Season 1 (inception)	Season 6 (end)
	Bulk density (0–30 cm) (g/m^2)	
Addition of unlabelled residue (T1)	1.41	1.38
Addition of labelled residue (T2)	1.39	1.36
Removal of unlabelled residue (T3)	1.36	1.39
Removal of labelled residue (T4)	1.39	1.41
SE (n = 32)	0.21	0.01
	Water-holding capacity (0–30 cm) (%)	
T1	25.8	26.2
T2	25.1	25.6
T3	24.5	22.8
T4	25.2	22.9
SE (n = 32)	0.14	0.43

3. RESULTS AND DISCUSSION

3.1. Experiment 1, impact of organic matter on N release and crop growth.

3.1.1. Soil parameters

The incorporation of residues affected soil parameters. At the end of six seasons in Experiment 1A and five seasons in Experiment 1B, which correspond to the two planting dates, the bulk densities of soils were marginally increased when crop residues were not added (Tables I and III) In contrast, incorporation of crop residues in Treatments 1 and 2 reduced bulk densities to some degree. This phenomenon was not evident in soils of plots cultivated without crop residues (Treatment 4). This could affect crop growth where reduced bulk density would facilitate better root growth [10]. Incorporation of crop residues in Treatments 1 and 2 maintained water-holding capacity of the soil after six seasons of continued cropping, in both experiments, which, again, facilitates crop growth. Absence of incorporation of crop residues reduced water-holding capacity.

Application of crop residues also increased soil organic matter (SOM) and CEC in Treatments 1 and 2 of the two experiments (Tables II and IV). This clearly confirmed the benefits of organic matter in maintaining soil productivity and quality, as described in earlier studies [11,12]. In addition, benefits would accrue to crop growth and yields [13].

3.2. Crop growth

3.2.1. Experiment 1A

The incorporation of crop residues as organic matter increased seed and straw yields of mung bean and corn significantly at the end of six seasons of continued relay cropping (Fig. 1). This demonstrated the importance of SOM in maintaining yields, and thus sustainability, of tropical cropping systems. In contrast, the removal of crop residues, as evidenced in Treatment 4, reduced seed and stover yields significantly, at the end of six seasons (Fig. 1).

Table II. Effect of organic matter incorporation on soil organic matter and CEC (Experiment 1A)

Treatment	Season 1 (inception)	Season 6 (end)
	Soil organic matter (0–30 cm) (%)	
T1	0.81	0.86
T2	0.89	0.92
T3	0.82	0.78
T4	0.80	0.77
SE (n = 32)	0.07	0.14
	Cation exchange capacity (0–30 cm) (mEq/100 g)	
T1	4.2	4.8
T2	4.2	4.6
T3	4.1	3.9
T4	4.0	3.5
SE (n = 32)	1.3	1.1

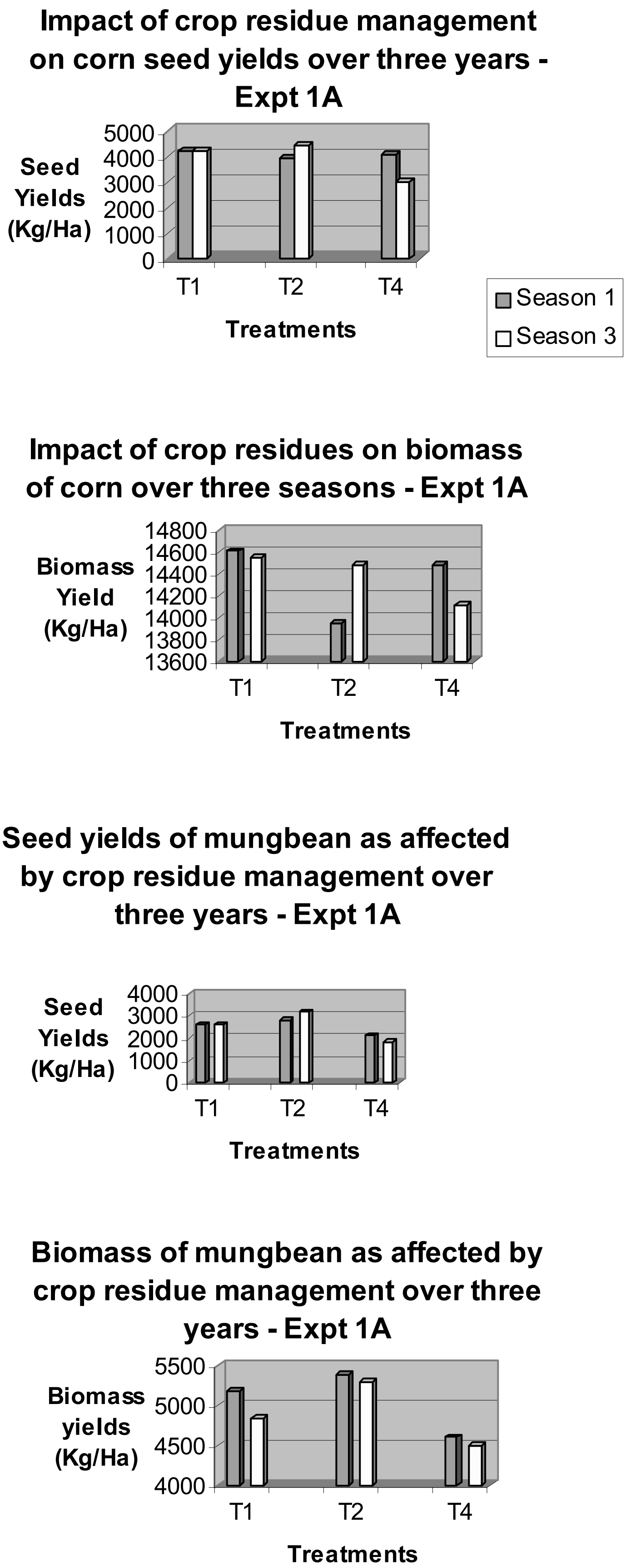


FIG. 1. Impact of crop-residue incorporation on seed and biomass yields of corn and mung bean (Experiment 1A). (Mung: grey bar= season 2, white bar=season 4)

In corn the yield reductions in seed and biomass at the end of the experiment were 20% and 3% respectively. In mung bean, the reductions in seed and biomass yields due to removal of crop residues were 14% and 3% respectively. This illustrated the greater importance of soil organic matter in sustaining yields of corn than of the legume, which has the capacity to fix atmospheric N_2.

Table III. Bulk density and water holding capacity of soil as affected by addition or removal of organic matter (Experiment 1B)

Treatment	Season 1 (inception)	Season 6 (end)
	Bulk density (0–30 cm) (g/m^2)	
T1	1.45	1.44
T2	1.39	1.42
T3	1.44	1.48
T4	1.37	1.42
SE (n = 32)	0.03	0.11
	Water-holding capacity (0–30 cm) (%)	
T1	24.7	25.6
T2	25.8	26.2
T3	24.9	24.0
T4	23.9	22.8
SE (n = 32)	1.41	0.97

Table IV. Effect of organic matter incorporation on soil organic matter and CEC (Expt 1B)

Treatment	Season 1 (inception)	Season 6 (end)
	Soil organic matter (0–30 cm) (%)	
T1	0.75	0.76
T2	0.84	0.86
T3	0.79	0.74
T4	0.81	0.76
SE (n = 32)	0.94	0.07
	Cation exchange capacity (0–30 cm) (mEq/100 g)	
T1	5.1	5.3
T2	4.8	5.0
T3	5.2	4.6
T4	4.7	4.5
SE (n = 32)	0.01	0.03

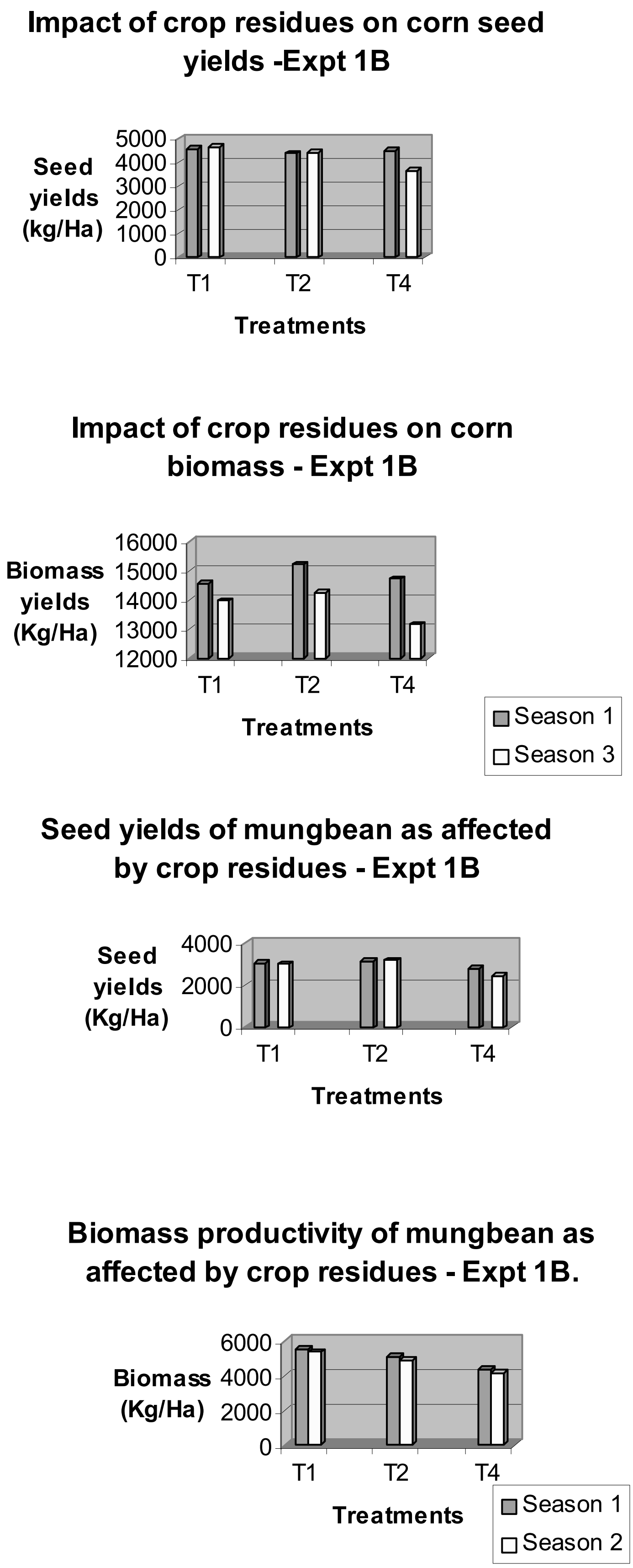


FIG 2. Impact of crop-residue incorporation on seed and biomass yields of corn and mung bean (Experiment 1B).

3.2.2 Experiment 1B

A similar phenomenon was also observed in yields in this experiment (Fig. 2). Again, the application of crop residues maintained or enhanced corn and mung bean yields over a period of five seasons. The removal of crop residues reduced yields of corn seeds and biomass by 19% and 10%, respectively, over the period of study. In mung bean, the removal of crop residues in Treatment 4 reduced yields of seed and biomass by 13% and 4%, respectively. This confirmed that the incorporation of crop residues enhances yields of corn to a greater extent, which could be considered a result of the improvement of soil parameters as illustrated in Tables I to IV

3.3. Nitrogen recovery

3.3.1. Experiment 1A

The pattern of recovery of applied N by corn and mung bean over the six seasons in Experiment 1A is presented in Fig. 3. As expected, ^{15}N enrichment of the crops declined with time.

In the first season, the percent recovery of applied N was higher in residues than seeds, which could be attributed to the large biomass accumulated by corn. This was evident in both treatments to which ^{15}N had been added.

Application of labelled fertilizer to Treatment 2 facilitated the enrichment of mung bean in season 2. However, due to the lower quantity of application of the labelled N, the degree of enrichment and the rate of ^{15}N recovery in mung bean were low. In contrast, the mung bean crop in Treatments 1 and 4 had a higher enrichment and greater recovery of ^{15}N due to residual effects. A comparison of rates of N recovery in Treatments 1 and 4 also illustrates a greater value in Treatment 1 due to the addition of crop residue. This was evident in all samplings, indicating that application of crop residues enhanced the recovery of applied N added in previous seasons, confirming a similar study using soybean as a green manure for buckwheat [14].

The recovery of the ^{15}N added in the first season declined most rapidly in the crop residue, as shown by the regression equations (Fig. 3). The lower %N recovery in seeds may have been a result of the large sink effect.

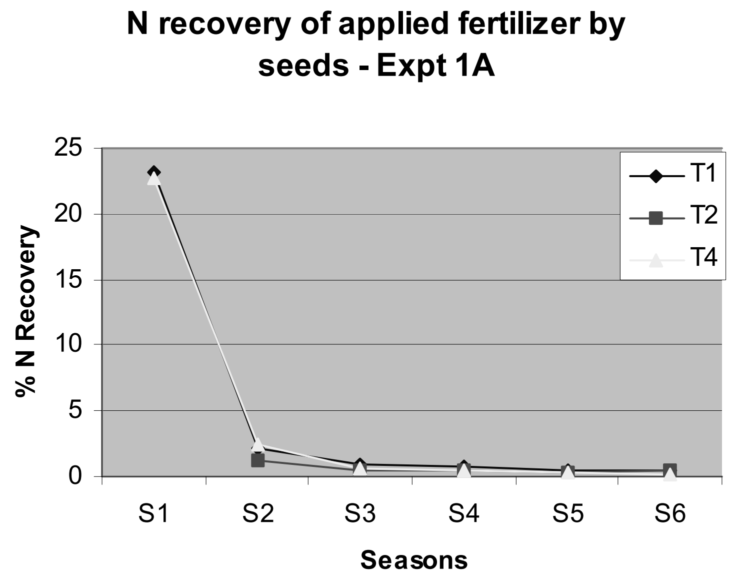
The rates of ^{15}N recovery were also greater in Treatment 1, as shown by the lower value of the slope of the regression equation. This indicates that the availability of ^{15}N was greater when crop residues were present in the soil. This highlights the importance of crop residues, or organic matter in general, to retain applied N, which can be rapidly lost in tropical cropping systems.

3.3.2. Experiment 1B

The patterns seen in Experiment 1A were also observed in this experiment (Fig. 4). However, the fraction of N recovered by the corn planted in the first wet season was greater than that of Experiment 1B, where the corn was planted in the dry season. In contrast, the N recovery by mung bean planted in the dry season in this experiment was lower than that of the same species planted in the wet season in Experiment 1A. The exception was in Treatment 2, where labelled residue was incorporated. The recovery rates of N are again greater in Treatment 1, with the application of crop residues. This confirms the benefits of applying organic matter in the form of crop residues in terms of better N availability and balance within the cropping systems.

3.4. Experiment 2

The soil moisture contents of soils in tubes varied with depth (Table V). The 30- to 50-cm soil layer had greater moisture content at all times. However, the quantity varied with rainfall.



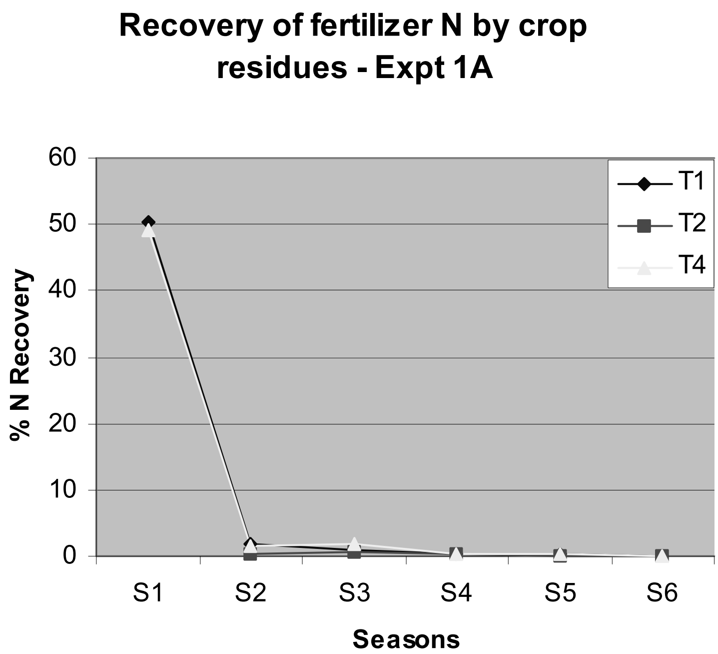
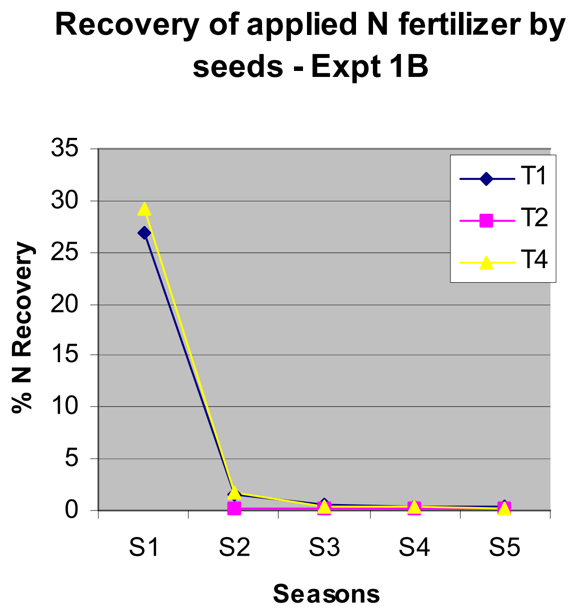


FIG. 3. Total recovery of applied ^{15}N by crop biomass over six seasons (Experiment 1A).

Seeds: T1 $Y = 16.342\ e^{-0.7194}X$, $R^2 = 0.7781$; T2 $Y = 1.4849\ e^{-0.2723}X$, $R^2 = 0.5939$;
T4 $Y = 20.474\ e^{-0.8635}X$, $R^2 = 0.8476$

Residues: T1 $Y = 57.817\ e^{-1.4087}X$, $R^2 = 0.7752$; T2 $Y = 0.4914\ e^{-0.4061}X$, $R^2 = 0.6954$;
T4 $Y = 72.578\ e^{-1.5213}X$, $R^2 = 0.8445$

Soil-N content did not vary significantly with the time of incorporation or sampling; declines over the 12-week period were marginal (Table VI). In contrast, the ^{15}N-excess values decreased with time. Incorporation of residue soon after harvest produced the highest level of soil-N enrichment at 3 weeks in the surface layer. This timing generally corresponded to the fallow period prior to planting the next crop. In the 15- to 30-cm layer of soil, the highest enrichment was also at 3 weeks, which could be attributed to the presence of the added organic matter. At 30 to 50 cm, the variation in ^{15}N enrichment was not significant with time, although a marginal increase was observed.



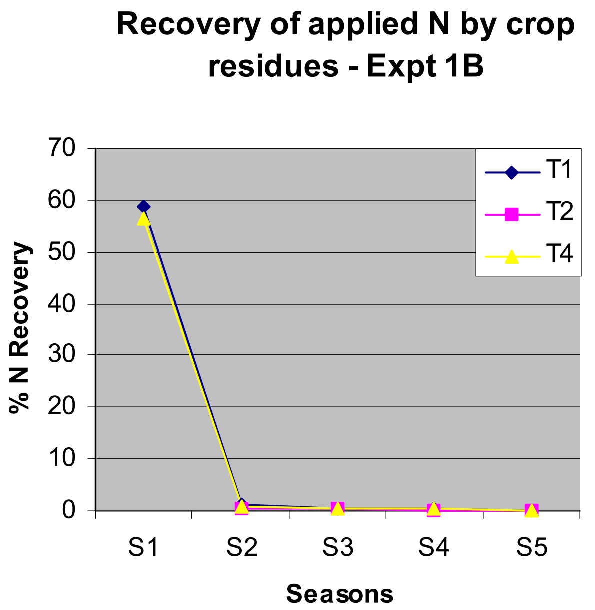


FIG. 4. Total recovery of applied ^{15}N by crop biomass over five seasons (Experiment 1B).

Seeds: T1 $Y = 26.776\ e^{-1.0105}X$, $R^2 = 0.7866$; T2 $Y = 0.41\ e^{-0.2775}X$, $R^2 = 0.6131$;
T4 $Y = 30.496\ e^{-1.1159}X$, $R^2 = 0.7817$

Residues: T1 $Y = 57.817\ e^{-1.4087}X$, $R^2 = 0.7752$; T2 $Y = 0.4914\ e^{-0.4061}X$, $R^2 = 0.6954$;
T4 $Y = 72.578\ e^{-1.5213}X$, $R^2 = 0.8445$

The addition of residue 2 weeks before planting produced the highest rate of enrichment at 6 weeks after planting in the surface layer of soil. This timing would correspond to the period of rapid crop growth, which would require N. In the next two layers of soil, the level of enrichment was higher at 6 weeks, but the changes were not significant. Thus, incorporation at 2 weeks before planting would provide N to the growing crop, by releasing nutrients to the top layer of the soil.

Table V. Variation in soil moisture with depth over 12 weeks

Time of incorporation	Depth (cm)	3 wks	6 wks	9 wks	12 wks
		(%)			
At harvest	0–15	15	10	12	15
	15–30	16	12	12	16
	30–50	16	13	13	17
SE		2.5	1.0	0.98	1.2
Two weeks before seeding	0–15	15	16	14	12
	15–30	16	17	14	13
	30–50	19	16	14	13
SE		0.85	2.5	0.28	1.4
At seeding	0–15	13	14	14	12
	15–30	13	14	15	13
	30–50	13	14	15	13
SE		3.1	0.47	0.82	1.3
Two weeks after seeding	0–15	14	16	12	13
	15–30	14	16	13	13
	30–50	14	17	13	13
SE		1.1	0.89	2.1	0.51

Table VI. Impact of time of incorporating organic matter on soil %N and %^{15}N excess with depth

Time of incorporation	Depth (cm)	Sampling dates							
		3 wks		6 wks		9 wks		12 wks	
		N	^{15}N excess	N	^{15}N excess	N	^{15}N excess	N	^{15}N excess
		(%)							
At harvest	0–15	0.14	0.092	0.14	0.081	0.13	0.074	0.13	0.049
	15–30	0.13	0.061	0.13	0.029	0.12	0.013	0.14	0.023
	30–50	0.11	0.012	0.14	0.022	0.12	0.019	0.11	0.022
Two weeks before seeding	0–15	0.14	0.087	0.12	0.107	0.14	0.084	0.12	0.067
	15–30	0.13	0.013	0.13	0.018	0.12	0.022	0.12	0.008
	30–50	0.12	0.009	0.11	0.019	0.13	0.018	0.11	0.011
At planting	0–15	0.14	0.061	0.12	0.092	0.13	0.092	0.13	0.076
	15–30	0.13	0.132	0.11	0.012	0.10	0.008	0.12	0.014
	30–50	0.11	0.029	0.10	0.012	0.12	0.023	0.09	0.013
Two weeks after planting	0–15	0.14	0.056	0.12	0.08	0.13	0.083	0.13	0.071
	15–30	0.13	0.018	0.12	0.009	0.13	0.015	0.12	0.019
	30–50	0.11	0.045	0.11	0.012	0.12	0.02	0.10	0.015

Incorporation of residue at planting produced the highest level of enrichment at 6 to 9 weeks in the topsoil layer. This would correspond to the flowering stage of a long-season cereal or the grain-development phase of a short-season legume. In the 15- to 30-cm layer, the highest level of enrichment was at 3 weeks, followed by a significant reduction. The changes at the deepest level were not significant.

Incorporation of crop residues at 2 weeks after planting also produced the highest level of enrichment between 6 and 9 weeks, in the topsoil. This timing would not be useful for a cereal or a legume crop. The levels of enrichment in the 15- to 30-cm and the 30- to 50-cm layers also did not indicate major changes.

4. CONCLUSIONS

This work, carried out over a period of 3 years, encompassed eleven seasons from two planting dates. The results clearly illustrate the benefits of incorporating organic matter for improving soil physical and chemical properties on a sustained basis.

Incorporating organic matter increased yields, both of corn and of mung bean. Analysis of plant samples grown with organic matter in plots supplied with ^{15}N fertilizer highlighted greater uptake of ^{15}N in later seasons, when compared with samples from plots grown only with the labelled fertilizer. This was another beneficial impact of incorporating organic matter.

The second experiment carried out in tubes buried in soil illustrated that application of organic matter had no significant effect on soil N to a depth of 50 cm. In contrast, the rate of release of ^{15}N changed with time. The addition of labelled organic matter showed that the ^{15}N enrichment of topsoil declined with time. In contrast, application of the enriched organic matter at 2 weeks before planting and sampling at 3-week intervals produced the highest levels of enrichment at 6 to 9 weeks after incorporation. This was evident when the organic matter was applied at planting or 2 weeks later. Thus, the addition of organic matter at 2 to 3 weeks before planting would release bound N to the growing crop especially within the surface layer of soil.

ACKNOWLEDGMENTS

Sincere gratitude is expressed to Dr. D.G. Keerthisinghe, the Scientific Officer of the project, for his guidance, advice and prompt attention. The support extended by the members of the Seibersdorf Laboratory in analysing samples, is gratefully appreciated. The financial and administrative support of the IAEA is acknowledged, along with the research assistance of Mr. P. Weerasekera and Mr. S. Kandapola. The University of Peradeniya provided infrastructure and some funding.

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MANAGEMENT OF ORGANIC MATTER AND NUTRIENT TURNOVER FOR INCREASED, SUSTAINABLE AGRICULTURAL PRODUCTION AND ENVIRONMENTAL PRESERVATION IN CHINESE RICE FIELDS

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Abstract

A field experiment was conducted in a rice-wheat cropping system to monitor (i) the fate of ^{15}N-labelled fertilizer with crop residues (T-1), (ii) the fate of ^{15}N-labelled crop residues (T-2), and (iii) the fate of ^{15}N labelled fertilizer without residues (T-4). Treatment T-3 was used to generate unlabelled crop residues. Crop recovery of applied ^{15}N in treatments T-1 and T-4 was about 37% in the first season, and, in the subsequent five cropping seasons, the recoveries were less than 2%. The total crop recovery for the six cropping seasons was about 40% for T-1 and T-4. About one-fourth of the applied ^{15}N was recovered in the soil in T-1 and T-4 plots; the recovery was about 5% higher in T-1 than in T-4. The total recovery of applied ^{15}N was 66% in T-1 and 62% in T-4 plots. In T-2, the crops recovered about 10% of N from the crop residues and 85% was retained by the soil, indicating a loss of about 5%. Crop N derived from fertilizer (NdfF%) in T-1 and T-4 was about 7% in the first cropping season, and less than 1% in the subsequent five seasons. The ratio of N derived from crop residue to the total N-uptake of wheat in T-2 plots was estimated at an average value of 12% in the first cropping season and less than 5% in the subsequent seasons. The NdfF% or NdfR% values for 0- to 50-cm soil depth showed contributions of fertilizer to total soil N accumulation of less than 0.5% in T-1 and T-4. The average yields of straw, grain and total DM for 1998, 1999, and 2000 in T-1 plots were about 16%, 7% and 12% higher than in T-4 plots, respectively. Application of crop residues showed a positive impact on the K uptake, soil-exchangeable K and NO_3 accumulation. Soil bulk density and soil moisture were not affected by straw application. Incubation experiments to examine the relationship between release of N from residues and N uptake by crops showed that application of residues immediately after sowing of wheat was more effective than at one month before sowing.

1. INTRODUCTION

The disposal of crop residues is a major problem in China. Since the 1980s, farmers and scientists have been examining various approaches. The total residue output in China varies from 500 to 600 Mt/year, equivalent to about 3 Mt of N, 0.7 Mt of P, and 7 Mt of K, i.e. one fourth of the total chemical fertilizer consumption. Burning rice straw is a major environmental concern due to emission of CO_2 and, therefore, there is an increased interest in various methods of recycling it. In the present study, we examined the effects of incorporation of rice straw on N nutrition and yields of rice and wheat. Results obtained for a 3-year cropping period are reported here; however, the trials are being continued to examine the sustainability of the system, because such information can be obtained only through long-term investigations [1,2].

2. MATERIALS AND METHODS

2.1. Design of Experiment A

Experiment A consisted of four treatments: (i) T-1, to monitor the flow and fate of ^{15}N-labelled fertilizer with crop residues; (ii) T-2, to determine the flow and fate of ^{15}N-labelled crop residues; (iii) T-3, to generate unlabelled crop residues; and (iv) T-4, to follow the flow and fate of ^{15}N-labelled fertilizer without crop residues. Treatments were established according to protocols drawn up at the first Research Co-ordination Meeting of this Co-operative Research Project. Nitrogen-15 was used as a tracer as described in [3] and [4].

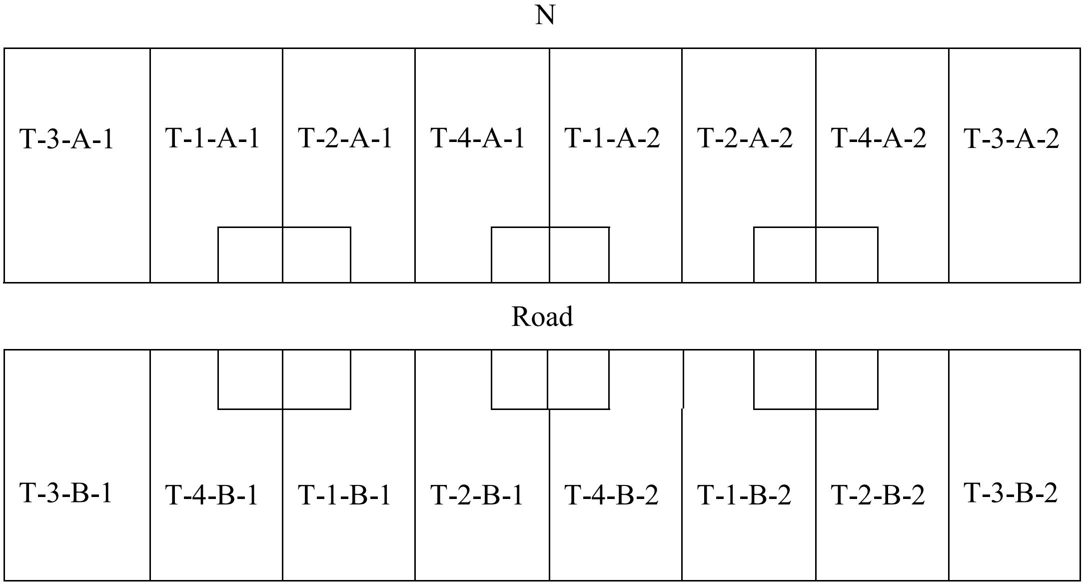

FIG. 1. The main-plot and microplot layout for Experiment A.

2.2. Layout of Experiment A

The main yield plots were 15×10 m and the ^{15}N-microplots were 4×4 m laid out as shown in Fig. 1. In the 1997 rice season, the total application rate of fertilizer N was 150 kg N/ha [60 kg ^{15}N-labelled $(NH_4)_2SO_4$ and 90 kg unlabelled $(NH_4)_2SO_4$]. It was applied 50% as basal and 50% as top dressing within 2 weeks of transplanting (or 2 months after sowing in the case of wheat). In the subsequent cropping seasons, the N fertilizer was applied at the same rates as in the first season, but was unlabelled. Phosphorus and K were applied at 50 kg/ha.

2.3. Soil

The soil in Experiment A is a heavy loam and a typical alluvial paddy soil (typical Haplaquept); basic properties are shown in Table I.

2.4. Location

Experiment A was established in the long-term experimental plots of the National Research Station of Soil Fertility and Fertilizer Efficiency on Paddy Soils, located at the experimental farm of Zhejiang Academy of Agricultural Sciences in Hangzhou, Zhejiang Province.

2.5. Climate

The climate is typical of the northern subtropical zone of China. Air temperature ranged from –7 to +39°C. The dry season is from September to March and the wet season is from April to August.

2.6. Experiment B

Experiment B was designed to monitor the decomposition dynamics of ^{15}N-labelled rice straw in soil, and N uptake by the winter wheat, in order to determine the most appropriate method of applying crop residues.

The treatments were as follows:

- Crop-residue rates: at soil:crop-residue weight ratios of 100:8 and 100:0.6.
- Times of crop-residue application: either 1 month before wheat sowing (stage I) or immediately before sowing (stage II).

Table I. Soil chemical properties, Experiment A

Property	Soil depth (cm)		
	0–15	15–30	30–50
Organic matter (%)	3.6	2.1	1.9
Total N (%)	0.199	0.060	0.046
Available N (mg/kg)	202	—	—
NH_4-N (mg/kg)	0.78	—	—
NO_3-N (mg/kg)	31.9	—	—
Total P_2O_5 (%)	0.257	—	—
Organic P_2O_5 (%)	0.033	—	—
$NaHCO_3$-P (mg/kg)	145	—	—
Exchangeable K (mg/kg)	118	—	—
Total salt (%)	0.0093	—	—
CEC (mEq/100g)	13.8	—	—
pH	6.88	—	—

The decomposition cylinders were porous carborundum tubes (length 15.5 cm, inside diameter 4.0 cm). Each tube was filled with 100 g dry soil and crop residues as indicated above. The ^{15}N abundance of the tested rice straw was 0.679% a.e., derived from T-1 microplots.

Experiment B was established in the T-4 main-yield plots. Eighty carborundum tubes were buried at 5 to 20 cm. The surface also was covered by wheat plants. Each treatment was replicated four times and sampling was at monthly intervals up to 5 months. The first-stage tubes were buried on 20 October 1998, 1 month before wheat sowing. The second-stage tubes were buried on 20 November 1998, at the time of wheat sowing.

The soil-residue mixture was sampled at 1, 2, 3, 4 and 5 months after wheat sowing for the analysis of total N, exchangeable ammonium (2 *M* KCl-extractable) as well as $\%^{15}N$ in the soil-residue mixture.

3. RESULTS AND DISCUSSION

3.1. Nitrogen recovery in the first season (1997, rice)

Values for %N recovery by the first crop, calculated by Eq. (1), are shown in Table II.

$$N\ recovery\ (\%) = \frac{^{15}N\ recovered\ by\ the\ crop}{^{15}N\ applied} \times 100 \qquad (1)$$

3.2. Soil-residual fertilizer N in the first season (1997, rice)

Values for % of N residual in the soil, calculated by Eq. (2), are shown in Table III.

$$Residual\ N\ (\%) = \frac{^{15}N\ remaining\ in\ the\ soil}{^{15}N\ applied} \qquad (2)$$

Table II. Fertilizer-N recovery for the first season in T-1 and T-4 plots (1997, rice)

Component	Treatment/Replicate			
	T-1			
	A-1	A-2	B-1	B-2
^{15}N recovered in grain (g/ha)	682	696	806	766
^{15}N recovered in straw (g/ha)	882	1073	1316	1098
^{15}N recovered in roots (g/ha)	531	265	308	268
Total ^{15}N recovered (g/ha)	2,095	2,033	2,430	2,131
Applied ^{15}N (g / ha)	5,934	5,934	5,934	5,934
N recovery (%)	35	34	41	36
Average N recovery (%)	37			
	T-4			
^{15}N recovered in grain (g/ha)	517	1,143	605	928
^{15}N recovered in straw (g/ha)	761	1,693	937	1,183
^{15}N recovered in roots (g/ha)	308	262	232	317
Total recovered ^{15}N (g/ha)	1,586	3,098	1,774	2,427
Applied ^{15}N (g/ha)	5,934	5,934	5,934	5,934
N recovery (%)	27	52	30	41
Average N recovery (%)	37			

Table III. Soil residual N in the first crop season (1997, rice)

Depth (cm)	Treatment	N in soil	^{15}N in soil	Soil wt. (t/ha)	^{15}N in soil	^{15}N input	Residual N (%)
		(%)			(g/ha)		
0–15	T-1	0.17	0.031	1,725	914	5,934	15
	T-4	0.20	0.034	1,725	1,173	5,934	20
15–30	T-1	0.14	0.011	2,291	353	5,934	6.0
	T-4	0.14	0.009	2,291	278	5,934	4.7
30–50	T-1	0.045	0.013	3,368	197	5,934	3.3
	T-4	0.063	0.009	3,368	191	5,934	3.2
0–50	T-1	—	—	—	—	—	25
	T-4	—	—	—	—	—	28

3.3. Total recovery of applied N in the first season (1997, rice)

Values for total recovery of fertilizer N, calculated by Eq. (3), are shown in Table IV.

$$Total\ N\ recovery\ (\%) = \frac{^{15}N\ in\ the\ crop + {}^{15}N\ remaining\ in\ the\ soil}{^{15}N\ applied} \times 100 \quad (3)$$

Table IV. Total recovery of fertilizer in the first season (1997, rice)

Treatment	Crop uptake	Soil residual	Applied	Crop uptake	Soil residual	Total recovery	Total loss
	(g ^{15}N/ha)			(%)			
T-1	2,173	1,470	5,934	37	25	61	39
T-4	2,221	1,593	5,934	37	28	65	35

Table V. Nitrogen-15 recovered by the second crop (1998, wheat)

Treatment	Straw	Grain	Total recovered
	(g ^{15}N /ha)		
T-1	24.4	42.9	67.3
T-2	10.8	22.5	33.3
T-4	21.2	48.2	69.4

Table VI. Soil residual ^{15}N in the second season (1998, wheat)

Depth (cm)	Treatment	N in soil	^{15}N in soil	Soil wt. (t/ha)	^{15}N in soil	Input ^{15}N	Residual N (%)
		(%)			(g/ha)		
0–15	T-1	0.21	0.045	1,725	1,616	5,934	27
	T-2	0.21	0.011	1,725	405	1,092	37
	T-4	0.21	0.029	1,725	1,091	5,934	18
15–30	T-1	0.16	0.007	2,291	241	5,934	4.1
	T-2	0.21	0.011	2,291	186	1,092	17
	T-4	0.17	0.007	2,291	268	5,934	4.5
30–50	T-1	0.080	0.009	3,368	242	5,934	4.1
	T-2	0.073	0.006	3,368	141	1,092	13
	T-4	0.080	0.006	3,368	162	5,934	2.7
0–50	T-1	—	—	—	—	—	35
	T-2	—	—	—	—	—	67
	T-4	—	—	—	—	—	26

3.4. Nitrogen recovery in the second crop (1998, wheat)

The ^{15}N recoveries during the second cropping season are shown in Table V, and the ^{15}N retained by the soil is shown in Table VI.

Table VII. Recovery of ^{15}N applied in the first season for the second season (1998, wheat)

Treatment	Crop uptake	Soil residual	Applied	Crop N uptake	Soil N residue	Total N recovery		Total loss
	(g ^{15}N/ha)			(%)				
T-1	67.3	2,099	5,934	1.1	35	36[a]	73[b]	27
T-2[c]	33.3	732	1,092	3.1	67	70[a]	70[b]	30
T-4	69.4	1,521	5,934	1.2	26	27[a]	64[b]	36

[a]For the second season. [b]For first plus the second seasons. [c]Values derived from the ^{15}N-labelled rice residue.

Table VIII. Crop recovery, and soil residual, and total recovery of applied ^{15}N in the third crop (1998, rice)

Treatment	Crop uptake	Soil residual	Applied	Crop N uptake	Soil N residual	Total N recovery		Total loss
	(g ^{15}N/ha)			(%)				
T-1	0.0412	2,012	5,934	0.69	35	36[a]	73[b]	27
T-2	0.0522	779	1,092	4.8	71	76[a]	79[b]	21
T-4	0.0526	1,619	5,934	0.89	29	30[a]	69[b]	31

[a]For the third crop. [b]For all crops.

Table IX. Crop recovery of applied fertilizer-N (1997–2000)

Component	Crop recovery of applied ^{15}N								
	1997 Rice			1998 Wheat			1998 Rice		
	T-1	T-4	T-2	T-1	T-4	T-2	T-1	T-4	T-2
	(%)								
Straw	24	24	–	0.41	0.36	0.98	0.32	0.39	2.2
Grain	12	13	–	0.72	0.81	2.06	0.38	0.49	2.6
Total	37	37	–	1.1	1.2	3.1	0.69	0.89	4.8
	1999 Wheat			1999 Rice			2000 Wheat		
Straw	0.23	0.22	0.29	0.20	0.15	0.41	0.02	0.01	0.04
Grain	0.39	0.49	0.90	0.43	0.35	0.83	0.02	0.02	0.05
Total	0.62	0.71	1.19	0.63	0.50	1.24	0.04	0.03	0.09

	Total crop recovery (1997 Rice to 2000 Wheat)		
	T-1	T-4	T-2
	(%)		
Straw	25	25	3.9
Grain	14	16	6.4
Total	40	41	10

Table X. Contribution of fertilizer-N/residue-N to plant N uptake (NdfF%/NdfR%, 1997–2000)

Treatment	1997 Rice	1998 Wheat	1998 Rice	1999 Wheat	1999 Rice	2000 Wheat
	(%)					
T-1[a] (S+G)[b]	6.6	0.72	0.24	0.24	0.17	0.020
T-2[c] (S+G)	0	12	4.6	2.6	1.2	0.24
T-4[a] (S+G)	7.0	0.92	0.33	0.30	0.15	0.019

[a]NdfF. [b]Straw+grain. [c]NdfR.

3.5. Soil-residual fertilizer N in the second crop (1998, wheat)

Values for % of N residual in the soil are shown in Table VI.

3.6. Total recovery of fertilizer ^{15}N in the second crop (1998, wheat)

Table VII shows the total recovery of fertilizer ^{15}**N** in various fractions.

3.7. Nitrogen-15 recovered by rice and soil in the third crop (1998, rice)

Recoveries of N in the crop, the soil, and in total are shown in Table VIII

3.8. Crop recovery of applied N (1997–2000)

Crop recoveries of applied N had values of approximately 37% for the first season and very small values in subsequent seasons (Table IX). No significant differences in crop recoveries of crop recoveries were observed between T-1 and T-4. The crops recovered less than 5% of the ^{15}N in the residues (T-2).

Values for NdfF% in T-1 and T-4 and NdfR% in T-2 are in Table X. Approximately 7% of plant N was derived from fertilizer in the first cropping season, and less than 1% subsequently. About 12% of plant N was derived from residues in the first cropping season.

3.9. Soil-residual ^{15}N (1997–2000)

Values of soil N (0 to 50 cm) residual from that applied as fertilizer and as residue for 1997 to 2000 are shown in Table XI.

The NdfF% or NdfR% values for 0 to 50 cm are shown in Table XII. The contributions of applied N to total soil N were less than 0.5% in T-1 and T-4 and less than 3% in T-2.

3.10. Total recovery of applied N (1997–2000)

Values for the recovery of applied ^{15}N from the 1997 rice crop to the 2000 wheat crop are shown in Table XIII. Total recovery in T-1 was higher than in T-4.

The application of crop residues resulted in increased recovery of applied fertilizer N. It is noteworthy that once the N was immobilized in soil, its availability remained low.

Table XI. Summary of soil residual N (1997–2000

Treatment	1997 Rice			1998 Wheat			1998 Rice		
	0–15[a]	15–30	30–50	0–15	15–30	30–50	0–15	15–30	30–50
	(%)								
T-1	15	6.0	3.3	27	4.1	4.1	28	5.5	1.1
T-2	—	—	—	37	17	13	50	13	8.1
T-4	20	4.7	3.2	18	4.5	2.7	23	4.1	2.1
	1999 Wheat			1999 Rice			2000 Wheat		
T-1	28	6.1	2.8	23	5.4	1.4	20	6.0	1.8
T-2	77	10.1	8.3	57	10	4.5	59	20	6.8
T-4	22	4.9	2.3	19	4.0	0.99	19	3.9	0.93

	1997 Rice	1998 Wheat	1998 Rice	1999 Wheat	1999 Rice	2000 Wheat
	0–50	0–50	0–50	0–50	0–50	0–50
T-1	25	35	35	37	30	28
T-2	—	67	71	96	72	86
T-4	28	26	29	30	24	24

[a]Soil depth (cm).

Table XII. The contributions of fertilizer-N and residue-N to total soil N at three depths (1997–2000)

Depth (cm)	Treatment	1997 Rice	1998 Wheat	1998 Rice	1999 Wheat	1999 Rice	2000 Wheat
		(%)					
(0–15)	T-1[a]	0.31	0.46	0.39	0.40	0.32	0.29
	T-2[b]	0	1.6	2.2	2.9	2.2	2.1
	T-4[a]	0.34	0.29	0.32	0.32	0.29	0.27
(15–30)	T-1	0.11	0.06	0.08	0.094	0.093	0.08
	T-2	0	1.6	0.51	0.42	0.45	0.70
	T-4	0.09	0.07	0.06	0.08	0.07	0.05
(30–50)	T-1	0.13	0.09	0.03	0.06	0.03	0.05
	T-2	0	0.85	0.60	0.55	0.38	0.44
	T-4	0.09	0.06	0.06	0.07	0.03	0.02

[a]NdfF. [b]NdfR.

3.11. Yields (1997–2000)

The crop yields in treatment T-1 were consistently higher than those in T-4, showing the positive effects of straw incorporation (Table XIV). For example, the yields of wheat grain, straw and total dry matter for T-1 were 5.3%, 23% and 11.5% higher than in T-4 plots in 1998 and, 5.5%, 5.2% and 5.4% higher than in T-4 for the 1998 rice crop. In summary, the average yields of straw, grain and total dry matter for the period 1998 to 2000 with T-1 were 16%, 7.0% and 11.5% higher than those with T-4.

Table XIII. Recovery of applied ^{15}N (1997–2000)

Component	Treat.	1997 Rice	1998 Wheat	1998 Rice	1999 Wheat	1999 Rice	2000 Wheat	Total
		(%)						
Crop uptake	T-1	37	1.1	0.70	0.62	0.63	0.04	40
	T-2	—	3.1	4.8	1.2	1.2	0.09	10
	T-4	37	1.2	0.89	0.71	0.5	0.03	41
Soil residual	T-1	25	35	35	37	30	28	28
	T-2	—	67	71	96	72	86	86
	T-4	28	26	29	30	24	24	24
Total recovered	T-1	61	37	36	38	30	28	68
	T-2	—	70	76	97	73	86	96
	T-4	65	27	30	30	25	24	64
Lost[a]	T-1	39	38	27	24	31	32	32
	T-2		30	21	–4.68	18	4.0	4.0
	T-4	35	34	31	30	35	36	36

[a]100 – (soil residue rate in the present crop season + crop recovery for the all crop seasons).

Table XIV. Crop yields (1997–2000)

Treatment	Straw			Grain			Total DM		
	T-1	T-2	T-4	T-1	T-2	T-4	T-1	T-2	T-4
	(t/ha)								
1997 Rice	11.0	9.22	11.5	6.60	6.09	6.73	17.6	15.3	18.2
1998 Wheat	3.86	2.01	3.12	2.95	1.87	2.81	6.81	3.88	5.93
1998 Rice	3.83	3.56	3.64	4.39	3.84	4.16	8.22	7.4	7.8
1999 Wheat	4.1	2.85	3.78	3.95	2.42	3.49	8.05	5.27	7.27
1999 Rice	3.99	3.37	3.14	7.04	5.82	6.75	11.0	9.19	9.89
2000 Wheat	7.12	4.58	6.05	3.52	2.75	3.21	10.6	7.33	9.26
Mean (seasons 1–6)	5.65	4.27	5.2	4.74	3.8	4.53	10.4	8.06	9.72
Mean (seasons 2–6)	4.58	3.27	3.95	4.37	3.34	4.08	8.95	6.61	8.03

3.12. Effects on uptake of P and K

Values for uptake of P and K with treatments T-1 and T-4 are shown in Table XV. Application of straw had positive effects on P and K nutrition both of rice and wheat. This was especially true for K, of which straw contains substantial quantities.

3.13. Effects on soil bulk density and soil moisture

The treatments had no marked effects on soil moisture or soil bulk density as determined after wheat harvest in May 2000 (Table XVI). The bulk density for 0 to 15 cm showed a slight decrease due to application of straw.

Table XV. Uptake of P and K in treatments T-1 and T-4 (1998–2000)

Treatment	Part	1998 Wheat		1998 Rice		1999 Wheat	
		P_2O_5	K	P_2O_5	K	P_2O_5	K
		(kg/ha)					
T-1	Straw	8.18	78.2	15.2	121	17.1	139
	Grain	12.6	25.5	20.7	28.8	33.1	21.9
	Total	20.8	103	35.9	150	50.2	161
T-4	Straw	6.73	73.4	15.9	119	15.5	96.2
	Grain	11.3	24.0	28.2	33.6	31.2	18.0
	Total	18.1	97.4	44.2	152	46.6	114
		1999 Rice		2000 Wheat		Mean 1998–2000	
T-1	Straw	39.0	128	26.5	208	21.2	135
	Grain	70.7	38.0	37.2	23.8	34.9	27.6
	Total	110	166	63.7	232	56.1	163
T-4	Straw	32.1	96.8	17.3	163	17.5	110
	Grain	67.6	28.2	30.4	20.2	33.8	24.8
	Total	99.7	125	47.8	183	51.	135

Table XVI. Soil bulk density and moisture content (May, 2000)

Depth (cm)	T-1		T-2		T-4	
	(g/cm^3)	(%)	(g/cm^3)	(%)	(g/cm^3)	(%)
0–15	1.09	41	1.12	41	1.10	41
15–30	1.33	36	1.34	34	1.33	35
30–50	1.49	28	1.55	26	1.55	27

3.14. Effects on soil exchangeable P and K, and on NH_4 and NO_3

The exchangeable P, K and mineral N contents in the 0- to 50-cm soil layer in T-1 and T-4 plots, after the harvest of wheat in May 2000, are shown in Table XVII. Exchangeable K and NO_3-N values in T-1 were higher than in T-4 plots, but no such differences were seen in soil exchangeable P or NH_4-N. Obviously, one of the main contributions of crop residue to soil fertility is the amount of K added in the straw.

3.15. Soil pH and CEC changes

Soil pH and CEC changes during the period of the 1997 rice season to the 1999 rice season are shown in Table XVIII. The results showed that application of crop residue had only minor decreasing effects on CEC and soil pH.

Table XVII. Soil exchangeable P and K and NH_4-N and NO_3-N after the harvest of wheat (May 2000)

Depth (cm)	Treat.	E-P[a] (mg/kg)	E-K[b] (mg/kg)	NH_4-N (mg/kg)	NO_3-N (mg/kg)
0–15	T-1	149	196	3.05	41.8
	T-4	145	162	3.75	33.3
15–30	T-1	48.1	56.4	2.98	12.5
	T-4	42.4	49.8	2.55	11.5
30–50	T-1	22.0	45.5	6.02	9.61
	T-4	21.3	51.2	4.40	9.38

[a]$NaHCO_3$-P. [b]NH_4OAC-K.

Table XVIII. Changes of pH and cation-exchange capacity (1997–1999)

Treatment/ Difference	1997 Rice		1998 Rice		1999 Rice	
	pH	CEC (mol/kg)	pH	CEC (mol/kg)	pH	CEC (mol/kg)
T-1	6.98	16.2	6.49	16.6	6.03	13.8
T-2	6.74	16.1	6.71	16.4	6.47	14.9
T-4	7.42	17.2	6.80	15.9	5.94	14.0
T-1–T-2	0.24	0.15	–0.23	0.20	–0.44	–1.15
T-4–T-2	0.69	1.1	0.090	–0.45	–0.53	–0.90
T-1–T-4	–0.45	–0.95	–0.32	0.65	0.09	–0.25

3.16. Experiment B

3.16.1. Release of N from the soil-residue mixture

The pattern of release of N from the soil-residue mixture is shown in Table XIX.

3.16.2. Nitrogen uptake by winter wheat

The pattern of accumulation of N by wheat from November 1998 to May 1999 is shown in Table XX.

3.16.3. Relationship of NH_4-N release from soil-residue mixture with crop N accumulation

Table XXI and Figs. 2 and 3 showed clearer correlations of crop N accumulation with NH_4-N in the soil-residue mixtures in I-2 and II-2 plots (R^2= 0.497 and 0.592, respectively) than in I-1 and II-1 plots (R^2 = 0.328 and 0.382, respectively). This indicates that the application of straw at sowing is better than at one month before sowing. The data in Table XXI are corrected for stubble and roots: the weight of the stubble was calculated as 0.25% of that of the straw and the weight of roots was assumed to be 0.3% of the straw weight.

Table XIX. Nitrogen in the soil and residue over time (January–April, 1999)

Stage/ Treatment[a]	N in the mixture of soil and residue			
	30-Jan-99	30-Feb-99	30-Mar-99	30-Apr-99
	(%)			
I-1	0.28	0.27	0.27	0.19
I-2	0.29	0.29	0.28	0.19
II-1	0.27	0.20	0.19	0.19
II-2	0.28	0.21	0.20	0.18

[a]I-1 and II-1=100:8 (soil:residue); I-2 and II-2=100:0.6.

Table XX. Dry matter and N accumulation in wheat over time (January–May, 1999)

Sampling time	Total DM (kg/ha)	Plant N (%)	N accumulation (kg/ha)
30-Jan-1999	950	4.2	40.2
30-Feb-1999	3,753	3.8	144
30-Mar-1999	17,771	2.4	421
30-Apr-1999	30,103	1.7	497
30-May-1999	8,125	2.0	165

Table XXI. The KCl-$^{15}NH_4$-N in the soil-residue mixture (January–May, 1999)

Treat.	30 Jan 99	30 Feb 99	30 Mar 99	30 Apr 99	30 May 99
	^{15}N in mixture (%)				
I-1	0.12	0.13	0.02	0.11	0.08
I-2	0.17	0.17	0.02	0.10	0.06
II-1	0.06	0.04	0.11	0.02	0.02
II-2	0.06	0.03	0.10	0.02	0.02
	KCl-N in mixture (mg/kg)				
I-1	2.5	1.25	10	1.25	8.8
I-2	14	2.0	2.5	2.5	3.6
II-1	3.1	2.5	8.9	2.3	7.9
II-2	10.7	2.1	2.4	2.3	3.1
	^{15}N/tube (μg)[a]				
I-1	12.2	13.7	1.44	9.49	6.58
I-2	13.2	10.2	1.68	7.57	5.66
II-1	5.86	3.90	6.90	1.81	1.64
II-2	4.33	1.91	7.11	1.69	1.82
	N accumulation by wheat (kg/ha)				
	40.2	144	421	497	165

[a]The soil-residue mixture was 108 g/tube in I-1 and I-2 and 101 g/tube in II-1 and II-2.

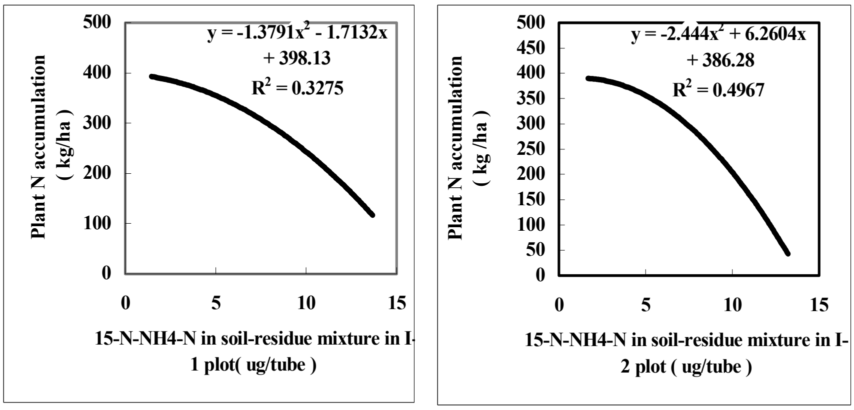

FIG. 2. $^{15}NH_4$ in soil-residue mixture in I-1and I-2 treatments of Experiment B.

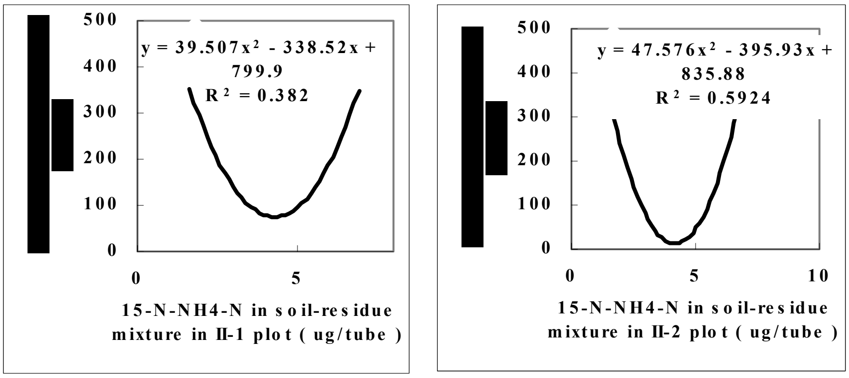

FIG. 3. The $^{15}NH_4$ in soil-residue mixture in II-1 and II-2 treatments of Experiment B.

Table XXII. Recalculation of total recovery and loss applied ^{15}N in T-1 and T-4 (1997–2000)

Component	Treat.	1997 Rice	1998 Wheat	1998 Rice	1999 Wheat	1999 Rice	2000 Wheat
		(%)					
Crop uptake	T-1	37	38	39	40	40	40
	T-4	37	39	40	41	41	41
Soil residual	T-1	25	27	29	33	26	25
	T-4	28	18	24	26	20	21
Total recovery	T-1	61	65	68	73	66	66
	T-4	65	57	64	67	62	62
Loss[a]	T-1	39	35	32	27	34	34
	T-4	35	43	36	33	38	38

[a]100% – (crop recovery + soil residual).

The data in Table XXII show that total recovery in T-4 was higher than that for T-1, probably as a result of retention of N due to application of straw in T-4.

4. CONCLUSIONS

Experiment-A data showed that the crop recoveries of applied fertilizer-^{15}N with treatments T-1 and T-4 were approximately 36% in the first crop season, and were less than 2% in the subsequent seasons. Total recovery of applied ^{15}N for the period of the 1997 rice crop to the 2000 wheat crop was 40% for T-1 and 41% for T-4. Thus, the application of crop residues did not show any significant effect on recovery of fertilizer N by crops.

In T-2 plots, for the period 1998 to 2000, the crops recovered about 10% of N from crop residues. Most of the N in the crop residues was immobilized in the soil.

About 25% of the applied N was retained in the soil in the 0- to 50-cm layer. At the end of the experiment in 2000, in T-1, about 5% more N was recovered in the soil than in T-4. These results show that application of residues increased immobilization of N.

In all seasons, application of residues increased the yields of straw, grain and total dry matter. The average yields of straw, grain and dry matter were 16%, 7% and 11.5% higher in T-1 than in T-4

The application of crop residues showed positive effects on P and K uptake by crops, especially of K. The high content of K in straw caused increased availability of K to crops in comparison to P.

Application of crop residues slightly decreased the soil bulk density of the topsoil but had no effect on soil moisture.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, and Drs. Chris van Kessel and Gamini Keerthisinghe (Scientific Secretary) for their support.

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NITROGEN USE AND EFFICIENCY IN A ROTATION WITH AND WITHOUT INCORPORATION OF CROP RESIDUES

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Abstract

A field experiment was conducted to study nitrogen (N) use and efficiency in a crop rotation with and without incorporation of residues under irrigated conditions. Nitrogen-15-labelled microplots were installed on a long-term experiment in which six rotations at two rates of fertilization are being examined. The rotation without incorporation of residues was maize-wheat-red clover-red clover; and the one with incorporation of residues was maize-wheat-common bean-barley. Treatments during the first growing season, when labelling maize (Experiment 1), were as follows: i) Treatment 1 (T1), determine the fate of ^{15}N-labelled fertilizer in the rotation with incorporation of residues. During subsequent seasons, only unlabelled residues were applied to these plots; ii) T2, determine the fate of ^{15}N-labelled residue with residues. Labelled residues were applied in the second growing season and, thereafter, unlabelled residues were used; iii) T3, determine the fate of labelled ^{15}N fertilizer in the rotation without residue incorporation—the control treatment for maize. During the second growing season (Experiment 2), the ^{15}N-labelled experiment was repeated and wheat (second crop in the rotation) was labelled. To label maize and wheat, 300 and 160 kg N ha^{-1} as ^{15}N-enriched urea and ammonium sulphate were applied, respectively. The labelled residues of maize and wheat were applied before sowing at 8,000 and 4,000 kg ha^{-1}, respectively. The same amounts of unlabelled residues were applied afterwards where appropriate. Results from both experiments showed similar trends and did not support the hypothesis that increased inputs of carbon lead to increased retention of N in the system. Possible explanations are discussed.

1. INTRODUCTION

Sustainable use of arable land implies conservation of soil organic matter (SOM) and associated soil micro-flora. Organic matter is essential to maintain the soil's capacity to regulate the availability of macro- and micro-nutrients [1]. Moreover, due to other multiple beneficial effects on soil biological, chemical, and physical properties, SOM is considered to be an important component of soil quality [2]. In the past, studies on organic matter and how it was affected by agricultural practices, emphasized soil fertility and crop productivity. More recently, SOM has become viewed as a potential source of atmospheric CO_2, therefore, conserving or increasing its content in the soil is justified not only from an agricultural perspective but also from an environmental point of view [2].

Organic matter content is strongly influenced by agricultural practices such as type and rotation, and management of crop residues [3,4]. Although changes in its content are easily measured in the long term, some components of SOM are sensitive to changes in the short term (e.g. biomass, light fraction), brought about by agricultural practices [5].

Important elements, particularly C, are returned to soil through management of crop residues, with effects on biological, chemical, and physical soil properties, e.g. activity of heterotrophic micro-organisms, cation -xchange capacity, water retention, soil aeration, and resistance to erosion [4,6].

In agricultural ecosystems, organic debris transformations (mineralization and humification) are regulated to various degrees by external (climate, soil, anthropogenic activity) and internal (crop-residue quality and quantity) factors. Their interactions regulate SOM dynamics, until a steady state is reached that is particular to each agricultural ecosystem [7].

Soils of volcanic origin in temperate zones present high contents of organic matter and organo-metallic complexes. Volcanic ash colloids contain very active Al and Fe components. These non-crystalline compounds can be present as mixtures of humic-clay complexes (allophane, imogolite, and ferrehydrite) or as organo-metallic complexes (humic-Al/Fe) often associated to opaline Si and crystalline clays. Many of the chemical and physical properties that control productivity in volcanic soils [8] are determined by these mineral components.

Soils of volcanic origin represent 50 to 60% of the arable land (5.4 Mha) in Chile. Located in various climates within the country, they are very important in wheat, sugar-beet, maize, oat, and cattle production [9]. Young volcanic-ash-derived soils called "trumaos"—once classified as Dystrandepts or Vitrandepts [10] and more recently as Andisols [8]—in the humid/sub-humid regions of the country (> 800 mm rainfall), have developed over basic ash from the Holocene or post-Würm period.

These soils present high content of allophane and of stabilized organic C, high P-fixation power, slightly acid pH [9], and large and very active microbial populations [11]. The organic N content, although also high, has a slow rate of mineralization. Furthermore, it has been postulated that allophanic constituents and Al and Fe amorphous compounds, together with local climatic conditions, will have a protective effect that promotes SOM accumulation [12,13]. However, mechanisms contributing to stabilization are poorly understood.

In Chile, straw burning is still common among farmers of small and large holdings cultivating annual cereals. Accordingly, soil fertility has decreased and the sustainability of these agricultural ecosystems is being questioned. Management of crop residues is an important agricultural practice, among others, that will help reverse this situation. The main objective is to effectively recycle crop residues and to increase the quantity of nutrients available to crops from organic sources. However, reports are rare on recovery of residue-N under varied management practices involving crop residues raised in situ [14].

A field experiment was conducted to study N use and efficiency in a rotation with and without incorporation of residues under irrigation conditions.

Table I. Precipitation and temperature data for the experimental site (25-year averages)

	Annual	Dry period[a]	Humid period[b]
Precipitation (mm)	1,042	192	849
Temperature (°C)	14		
Maximum		27	15
Minimum		9.1	4.9

[a]October–March. [b]April–September.

Table II. Chemical properties of the soil

Source	pH[a]	N total	OM	NH_4	NO_3	Av. P[b]	K	Ca	Mg	Na
		(%)		(mg kg^{-1})				(cmol kg^{-1})		
Rotation (–)[c]	5.16	0.46	8.7	96.4	17.0	11.4	0.17	4.0	0.56	0.33
Rotation (+)[d]	5.75	0.43	9.0	44.6	13.7	12.3	0.33	4.8	0.54	0.35

[a]In water.
[b]Extracted with Olsen's solution.
[c]Maize-wheat-red clover, without incorporation of residues.
[d]Maize-wheat-common bean-barley, with incorporation of residues.

Table III. Physical properties of the soil

	Sand	Silt	Clay	Bulk density (g cc^{-1})
		(%)		
Serie Diguillin (Santa Rosa)	73	23	3.4	1.08

2. MATERIAL AND METHODS

2.1. Experimental site

The experiment was conducted at Santa Rosa Experimental Station of the National Institute for Agricultural and Livestock Research (INIA-Quilamapu), which is located in the Central Valley of the south-central region of Chile (36°31'34" S, 71°54'40" W). Average precipitation and temperatures are shown in Table I.

2.2. Soil

The soil, of volcanic origin, is classified as a Typic Melanoxerand (Andisol). Chemical and physical properties are shown in Tables II and III. Allophane and ferrhydrite components are shown in Table IV. Extractable Al, Fe, Si and allophane were estimated in three layers (0–20, 20–60 and 60–90 cm) of the soil profile. Soil was extracted with 0.2 *M* ammonium oxalate buffered at pH 3 by oxalic acid, and Al, Fe, and Si (Al_o, Fe_o, Si_o) were measured by atomic absorption spectrometry (AAS). Briefly, 1 g of air-dry soil was treated with 80 mL of extractant after shaking for 4 h at 20°C in the dark [15]. Extracts were centrifuged at 5,000 rpm for 5 min, and Al Fe and Si in the supernatant were determined by AAS. Similar soil samples were extracted with 0.1 *M* Na pyrophosphate (pH 10), after 16 h shaking. One gram of air-dried soil was extracted with 100 mL Na pyrophosphate and centrifuged for 20 min at 18,000 rpm. Aluminium, Fe, and Si (Al_p, Fe_p, Si_p) were determined by AAS as described earlier. Allophane estimates were calculated from the relationships between Al_o, Al_p and S_o according to Aran [15] and Parfitt and Henmi [16] (see also Table IV). Ferrihydrite content was calculated by the formula proposed by Childs [17]:

$$\text{ferrihydrite (\%)} = Fe_o(\%) \times 1.7$$

Table IV. Percentage of Al, Fe and Si, extracted by ammonium acid oxalate and Na pyrophosphate in the volcanic soil used in this study (allophane and ferrihydrite estimates calculated by using Al/Si ratios and %Fe, respectively)

	Oxalate extraction			Pyro-phosphate extraction				Allophane							
									(Al/Si=2/1)[b]						
Depth (cm)	Al_o	Fe_o	Si_o	Al_p	Fe_p	Si_p	$\frac{Al_o\text{-}Al_p{}^{a}}{Sio}$	FM^2	Al_o	Al_{o-p}	Si_o	Ferri-hydrite	$\frac{Al_p}{Al_o}$	$\frac{Fe_p}{Fe_o}$	Al_o+ $1/2Fe_o$
	(%)							%							
0–10	2.28	0.74	0.52	0.64	0.27	0.04	3.3	7.5	8.4	6.0	3.7	1.3	0.28	0.36	2.6
10–36	2.54	0.66	0.59	0.63	0.21	0.05	3.3	8.5	9.3	7.0	4.2	1.1	0.25	0.31	2.9
36–60	1.28	0.76	0.35	0.35	0.28	0.03	2.8	3.9	4.7	3.4	2.5	1.3	0.27	0.36	1.7

[a]Atomic ratio $[(Al_o–Al_p)/Si_o]×28/27$, used to calculate allophane content ($FM×Si_o$). In this study the molar ratio is 3.3 and 2.8 and the corresponding FM is 14.4 and 11.2, respectively [15].
[b]To estimate allophane content by using $\%Al_o$ and $\%Al_o–Al_p$, a maximum value of 27.2% Al is taken (imogolite reference). When using Si_o (%) the Si maximum value is 14.1% Si [16].

2.3. Experiment design

Microplots to be labelled were installed on a long-term experiment (main experiment), under irrigated conditions, started 1992, in which six rotations (main plots) at two rates of fertilization (sub-plots) and with four replicates (blocks) are being tested. Two rotations were used: i) without incorporation of residues that included maize-wheat-red clover-red clover; and ii) with incorporation of residues that included maize-wheat-common bean-barley. When the experiment was established,all rotations were 4 years old (i.e. one four-crop sequence had been completed).

Macroplot sizes, with corresponding rotations, were 560 m^2 (40×14 m). Microplots installed on sub-treatments with high-level fertilization (sub-plots were 7×40 m) were confined to one end of the sub-plots, corresponding to an area of 70 m^2 (7×10 m).

2.4. Layout

2.4.1. Experiment 1

Treatments applied in the first growing season, when labelling maize (year 1), were as follows:

— Treatment 1 (microplot T1M-Y1), to determine the fate of ^{15}N-labelled fertilizer in the rotation with incorporation of residues; during subsequent seasons only unlabelled residues were applied to these plots.
— Treatment 2 (microplot T2M-Y2), to determine the fate of ^{15}N-labelled residue with residues; labelled residues were applied in the second growing season (year 2, wheat) and thereafter unlabelled residues were applied.
— Treatment 3 (microplot T3M-Y1), to determine the fate of labelled ^{15}N fertilizer in the rotation without residue incorporation; control treatment for maize.

The microplots were 9.7 m^2 (2.7×3.6 m) in area. To label maize, 300 kg N ha^{-1}, 5.06 atom % ^{15}N excess, were applied as a urea solution. One application was made when the plants were 40 to 50 cm in height.

2.4.2. Experiment 2

During the second growing season, the experiment was repeated and wheat (the second crop in the rotation) was labelled with ^{15}N. Treatments were as follows:

— Treatment 1 (microplot T1W-Y2), to determine the fate of ^{15}N-labelled fertilizer in the rotation with incorporation of residues; during subsequent seasons only unlabelled residues were applied to these plots.

— Treatment 2 (microplot T2W-Y3), to determine the fate of ^{15}N-labelled residue with residues; labelled residues were applied for the third growing season (year 3, common bean) and unlabelled residues thereafter.

— Treatment 3 (microplot T3W-Y2), to determine the fate of labelled ^{15}N fertilizer in the rotation without residue incorporation; control treatment for wheat.

The microplots was 6.25 m^2 (2.5×2.5 m) in area, and to label wheat 160 kg N ha^{-1} as ammonium sulphate (6.72 at%^{15}N enrichment) were applied at tillering.

The bean and red clover plots during the third growing season were 4.5 m^2 (1.5×2.5 m in area). Barley and red clover in the fourth growing season were sown using a no-till machine together with main plot microplot sizes conserved.

2.5. Residue enrichment (Treatment 2)

The rate of labelled maize residues in Experiment 1 was 800 g m^{-2} (equivalent to 8,000 kg ha^{-1}), applied before sowing. The same amount of unlabelled residues was applied as appropriate. Wheat-residue rate in Experiment 2 was 400 g m^{-2} (4,000 kg ha^{-1}), applied before sowing.

2.6. Soil sampling

Samples of surface soil (0–20 cm) were taken before sowing and application of fertilizers, and at harvest time at three depths (0–15, 15–30, 30–50 cm).

2.7. Plant sampling

For maize the harvest area in the first growing season (Experiment 1) was 4.275 m^2 (2.25×1.90 m), about 44% of the total area of each microplot. In the case of wheat in the second growing season (Experiment 2), microplots T1W-Y2 and T3W-Y2, the area harvested was about 3.0 m^2. The same area of each microplot was used where labelled maize residues were applied (T2M-Y2, second growing season). The bean-harvest area in the third growing season was 1.5 m^2 (1×1.5 m). Red clover was sampled (1 m^2) twice (first and third cuts) during the third growing season and only once (last cut) during the fourth season. The yield for barley in the fourth growing season, in the rotation with incorporation of crop residues, was taken as the average of five samples of 1 m^2 each in the main plot. The harvested area after the first growing season in established microplots, T1M-Y1 and T3M-Y1, was about 4.5 m^2.

2.8. Analyses

At harvest time, plant dry matter was determined after drying the material at 60°C. Soil was air-dried and plant and soil material were finely ground (<250 µm) for total N and ^{15}N analyses, which were achieved by dry combustion and mass spectrometry, respectively [18].

2.9. Methods of calculation

The formulae given by Zapata [19] were used to estimate amount of N in the crop derived from fertilizer, amount of N remaining in the soil, and ^{15}N recovery in the plant-soil system.

2.10. Statistical analysis

All analyses were performed using the STATISTICA package for Windows, Version 5.5 (Basic Statistics and ANOVA/MANOVA modules) [20].

Two-sample t tests were made to compare treatment means presented in Tables X and XII (e.g. labelled-N), and in Figs. 3 to 6 (i.e. ^{15}N recovery in plant + soil). Estimates shown in figures were analysed by year or at the end of the three or two years for Experiments 1 and 2, respectively. For the later analyses, ^{15}N amounts recovered in the plants during the 3 or 2 growing seasons plus ^{15}N amounts retained in the soil at the end of the crop cycle were considered. Total ^{15}N recovery (plant + soil) determinations for the two first years in Experiments 1 and 2 were also combined and submitted to a three-factor (experiment, treatment, year) analysis of variance. Despite the few available data, a two-sample test was made to compare treatments means T1 plus T2 versus T3. It was considered that T1 represents belowground ^{15}N recovery and T2 presents aboveground ^{15}N recovery.

Two-sample t tests were made to compare treatment means presented in Tables V, VII, IX and XI (e.g. dry matter). Only 2 years (maize-wheat) of results were analysed in Experiment 1 and only year 1 in Experiment 2, since year 3 and 2 for Experiments 1 and 2, respectively, presented different crops. Total 2-year dry-matter estimates of Experiment 1 (T1 and T3) were also submitted to a two-factor (treatment and year) analysis of variance. This model was considered better than the two-sample test made by year.

3. RESULTS AND DISCUSSION

3.1. Dry matter and N contents

Plant-component dry matter yields and N contents for Experiment 1 are shown in Tables V and VI respectively (see also Table VIII). Similar estimates for Experiment 2 are presented in Tables VII and VIII (see also Table IX). Maize yields, after one 4-year crop-sequence cycle, were similar among treatments, with and without incorporation of residues (Tables V and IX). Total dry-matter contents were not significantly different (P=0.3368). However, yield of following unfertilized wheat (Table V) was significantly lower with incorporation of maize residues than where residues were not recycled (P=0.0076). The most probable explanation is that N immobilization was caused by low N-content maize stalks (0.48% N, Table VI) that were incorporated just before sowing wheat. Thus, the crop was strongly affected in the first stages of the growing period. On the other hand, when wheat was fertilized in plots established in the main experiment after a 5-year crop sequence (e.g. Table VII, see also Table XI), yields were higher in the treatment incorporating residues than without their incorporation, and the difference was significant (P=0.0062).

Comparison of total dry-matter yields in both treatments (rotations) after two growing seasons (maize and wheat) showed, as stated earlier, that when the following crop was not fertilized, significantly lower yields were obtained (P=0.0261) in the treatment T1M-Y1 than in treatment T3M-Y1. The difference was about 4 t ha^{-1} (Table V). In contrast, when the following crop in the sequence was fertilized, e.g. T1W-Y2 and T3W-Y2 (Table XI), yields were higher for the former treatment than for the latter, but the difference was small (about 1 t ha^{-1}, Tables IX and XI). The comparison of both experiments (e.g. different wheat N-management following maize) showed a clear experiment-treatment interaction (P=0.0236) and suggested that no dry-matter yield decreases occurred when wheat was fertilized.

Table V. Plant-component dry weights of four sequential crops (Experiment 1) in two rotations, with or without incorporation of residues

Rotation	Dry matter			
	Plant part 1[a]	Plant part 2[b]	Plant part 3[c]	Plant part 4[d]
	(t/ha)			
With residues				
Maize	8.41 (0.59)[e]	1.71 (0.24)	8.65 (1.48)	
Wheat	2.25 (0.38)	1.58 (0.29)		
Bean	0.494 (0.09)	0.720 (0.16)	1.55 (0.30)	
Barley	7.88 (0.90)	6.19 (0.71)		
Without residues				
Maize	9.81 (0.81)	1.87 (0.25)	8.85 (1.68)	
Wheat	4.11 (0.94)	2.63 (0.41)		
Red clover	1.65 (0.71)	2.70 (0.63)	1.92 (0.54)	1.45 (0.33)
Red clover	2.50 (0.20)	2.35 (0.19)	0.675 (0.19)	1.05 (0.25)

[a]Maize=stalk, wheat=straw, bean=stems, barley=straw, clover=first cut.
[b]Maize=ear, wheat=grain, bean=pods, barley=grain, clover=second cut.
[c]Maize=kernels, bean=grain, clover=third cut.
[d]Clover=fourth cut. [e]SD (n=4).

Table VI. Nitrogen contents of four sequential crops (Experiment 1) in two rotations, with or without incorporation of residues

Rotation	Nitrogen			
	Plant part 1[a]	Plant part 2[b]	Plant part 3[c]	Plant part 4[d]
	(%)			
With residues				
Maize	0.48 (0.05)[e]	0.34 (0.04)	1.53 (0.11)	
Wheat	0.24 (0.03)	1.68 (0.12)		
Bean	1.02 (0.33)	0.82 (0.09)	3.30 (0.44)	
Barley	0.65 (0.08)	1.12 (0.05)		
Without residues				
Maize	0.63 (0.09)	0.35 (0.04)	1.54 (0.08)	
Wheat	0.25 (0.02)	1.53 (0.06)		
Red clover	2.97 (0.13)	ND[f]	2.70 (0.31)	ND
Red clover	ND	ND	ND	2.32 (0.53)

[a]Maize=stalk, wheat=straw, bean=stems, barley=straw, clover=first cut.
[b]Maize=ear, wheat=grain, bean=pods, barley=grain, clover=second cut.
[c]Maize=kernels, bean=grain, clover=third cut.
[d]Clover=fourth cut. [e]SD (n=4). [f]Not determined (in microplots).

Table VII. Plant-component dry weights of three sequential crops (Experiment 2) in two rotations, with or without incorporation of residues

Rotation	Dry matter			
	Plant part 1[a]	Plant part 2[b]	Plant part 3[c]	Plant part 4[d]
	(t ha^{-1})			
With residues				
Wheat	7.85 (0.31)[e]	5.35 (0.90)		
Bean	0.377 (0.11)	0.495 (0.12)	0.834 (0.17)	
Barley	7.88 (0.90)	6.19 (0.71)		
Without residues				
Wheat	5.89 (0.53)	4.31 (0.52)		
Red clover	1.65 (0.71)	2.70 (0.63)	1.92 (0.54)	1.45 (0.33)
Red clover	2.50 (0.20)	2.35 (0.19)	0.675 (0.19)	1.05 (0.25)

[a]Wheat=straw, bean=stems, barley=straw, clover=first cut. [b]Wheat=grain, bean=pods, barley=grain, clover=second cut. [c]Bean=grain, clover=third cut. [d]Clover=fourth cut. [e]SD (n=4).

Table VIII. Nitrogen content of three sequential crops (Experiment 2) in two rotations, with or without incorporation of residues

Rotation	Nitrogen			
	Plant part 1[a]	Plant part 2[b]	Plant part 3[c]	Plant part 4[d]
	(%)			
With residues				
Wheat	0.30 (0.04)[e]	1.90 (0.20)		
Bean	1.23 (0.41)	0.84 (0.26)	3.10 (0.52)	
Barley	0.66 (0.06)	1.28 (0.13)		
Without residues				
Wheat	0.37 (0.03)	1.97 (0.07)		
Red clover	3.03 (0.31)	ND[f]	2.47 (0.55)	ND
Red clover	ND	ND	ND	2.31 (0.31)

[a]Wheat=straw, bean=stems, barley=straw, clover=first cut. [b]Wheat=grain, bean=pods, barley=grain, clover=second cut. [c]Bean=grain, clover=third cut. [d]Clover=fourth cut. [e]SD (n=4). [f]Not determined (in microplots).

Differences in bean yields between Experiments 1 and 2 (Tables V and VII) were significantly higher in the former (P=0.0088) than in the latter. These results were consistent with beans yields obtained in treatment T2W-Y3 (cultivated beans on recycled labelled wheat straw) and reflect a distinct N contribution from incorporated residues, due both to the number of growing seasons and immobilization-mineralization processes. In our conditions, biological N_2 fixation in beans was insufficient for good yields and there was a need for a complementary inorganic fertilization at flowering.

Nitrogen contents in Experiments 1 and 2 (Tables VI and VIII, respectively) showed, as usual, higher content in the grain component than in the straw. Also, leguminous plants presented higher N contents than did non-legumes. Labelled residues used in Treatment 2 (T2) were low in N content, 0.49±0.05 and 0.30%±0.04, for maize and wheat respectively. Corresponding atom % ^{15}N excess values were 1.94 and 4.35 (Tables IX and XI).

3.2. Fertilizer N utilization and ^{15}N recovery in maize and soil (Experiment 1)

During the first growing season in Experiment 1 (when labelling) ^{15}N recovery at harvest was used to calculate fertilizer-N utilization (or recovery by the crop), and ^{15}N recovery in plants plus soil (Table X). Results showed only small differences in ^{15}N recovery by the crops between treatments, with somewhat higher amounts in the treatment incorporating residues (P=0.2930). Similar results were found in the soil (0–50 cm depth). There were no significant differences between treatments (P=0.9698). Total ^{15}N recovery (plant + soil) was about 14% higher (Table X) in treatment T1M-Y1 with incorporation of residues compared to without incorporation (T3M-Y1); however, the difference was not significant (P=0.8320). Corresponding unaccounted-for ^{15}N (losses) were 17 and 30% and were considered moderate.

Nitrogen-15 recovered by maize was low (21–24%) in both treatments. Fertilizer-N utilization by maize in Latin America and the Caribbean Region has been reported to range between 19 and 89%, depending on climate, soil, treatment and agricultural management [21]. Lower values are usually associated with lower yields resulting from water or nutrient deficiency. However, other studies under irrigated conditions and fertile soils and with high grain yields, as in this study, have also found lower plant recovery. As discussed in those studies, it is probable that high native soil-N availability is causal [21], indicating that, in our conditions, 300 kg N applications were very high. Due to dilution effects with soil N, relative availability of fertilizer N to plants is decreased. It is also known that, under normal conditions, nutrient-recovery efficiency decreases significantly with the nutrient rate applied. On the other hand, the absence of a zero-N treatment unfortunately prevented calculation of N recovery by the difference method. Rao et al. [22] found that N recovery efficiency (NRE) values estimated by the isotope-dilution method can be 20% lower than those estimated by the difference method due to an apparent added-N interaction (ANI) effect (substitution of ^{15}N for ^{14}N in the immobilization and denitrification processes). Increased soil-N uptake and positive ANI effects, observed with increased rates of N fertilization, have been reported elsewhere [22–24].

Table IX. Dry weights and N content of maize stalks, shelled ears and kernels in two rotations, with or without incorporation of residues (N applied as urea, 300 kg N ha^{-1})

Plant part	With residues[a]		Without residues[b]	
	Dry weight (t ha^{-1})	N content[c] (%)	Dry weight (t ha^{-1})	N content (%)
Stalk	8.45 (0.51)[d]	0.49 (0.05)	9.81 (0.70)	0.63 (0.09)
Shelled ear	1.71 (0.21)	0.34 (0.04)	1.87 (0.22)	0.35 (0.04)
Kernel	8.65 (1.28)	1.53 (0.11)	8.85 (1.45)	1.54 (0.08)
Total	18.8		20.5	

[a]**Maize**-wheat-common bean-barley. [b]**Maize**-wheat-red clover-red clover. [c]At. %^{15}N exc. with residues: stalk=1.94 (0.16); shelled ear=2.27 (0.28); ear=2.14 (0.23). Without residues: stalk=1.63 (0.34); shelled ear=1.71 (0.37); ear=1.58 (0.30). [d]SD (n=4).

Table X. Amounts of ^{15}N and unlabelled N in soil and the stalks, shelled ears and kernels of maize in two rotations, with or without incorporation of residues (N applied as urea, 300 kg N ha^{-1}, 5.06% ^{15}N excess)

Compartment	With residues[a]		Without residues[b]	
	Labelled	Unlabelled	Labelled	Unlabelled
	($kg\ ha^{-1}$)			
Stalk	15.6 (1.30)[c]	25.1 (2.46)	19.4 (2.17)	42.3 (8.40)
Shelled ear	2.58 (0.37)	3.20 (0.64)	2.27 (0.78)	4.30 (0.61)
Kernal	55.1 (1.36)	76.9 (14.2)	42.5 (10.8)	92.8 (13.5)
Total	73.2	105	64.2	139
Soil (0–50)	176 (38.2)		144 (32.1)	
	NUE[d] (%)			
	24 (0.83)		21 (4.4)	
	^{15}N recovery[e] (%)			
	83		70	

[a]**Maize**-wheat-common bean-barley. [b]**Maize**-wheat-red clover-red clover. [c]SD (n=4). [d]Nutrient uptake efficiency. [e]Plant+soil.

Table XI. Dry weights and N content of grain and straw of wheat in two rotations, with or without incorporation of residues (N applied as ammonium sulphate, 160 kg N ha^{-1})

Plant part	With residues[a]		Without residues[b]	
	Dry weight	N content[c]	Dry weight	N content
	($t\ ha^{-1}$)	(%)	($t\ ha^{-1}$)	(%)
Stalk	7.85 (0.31)[d]	0.30 (0.04)	5.89 (0.53)	0.37 (0.03)
Grain	5.35 (0.90)	1.91 (0.20)	4.31 (0.52)	1.98 (0.07)
Total	13.2		10.3	

[a]Maize-**wheat**-common bean-barley. [b]Maize-**wheat**-red clover-red clover. [c]At. %^{15}N exc. With residues: straw=4.35; grain=4.19. Without residues: straw=3.82; grain=3.78. [d]SD (n=4).

3.3. Fertilizer-N utilization and ^{15}N recovery in wheat plants and soil (Experiment 2)

During the second growing season, wheat plants were labelled (Experiment 2, T1W-Y2 and T3W-Y2). As with Experiment 1, ^{15}N recovery at harvest was used to calculate fertilizer-N utilization (or recovery by the crop), and ^{15}N recovery in wheat plants plus soil (Table XII). Results showed important differences in ^{15}N recovered by the crops between treatments, with higher amounts in the treatment incorporating residues (P=0.0698). Differences found in the soil (0–50 cm depth) were not significant. However, ^{15}N retained in the soil at 0 to 50 cm depth was significantly higher in T1 (P=0.0129) than in T3. Total ^{15}N recovery (plant + soil) was about 17% higher (Table XII) in T1W-Y2 with incorporation of residues compared to without incorporation (T3W-Y2). The difference was not significant (P=0.5272).

Table XII. Amounts of ^{15}N-labelled and unlabelled N in soil and in the straw and grain of wheat in two rotations, with or without incorporation of residues (N applied as ammonium sulphate, 160 kg N ha^{-1}; 6.72% ^{15}N excess.)

Compartment	With residues[a]		Without residues[b]	
	Labelled	Unlabelled	Labelled	Unlabelled
	(kg ha^{-1})			
Straw	15.3 (2.45)[c]	8.20 (1.24)	12.4 (1.78)	9.30 (0.48)
Grain	63.1 (10.0)	37.8 (7.55)	48.0 (6.60)	37.0 (3.36)
Total	78.3	46.0	60.5	46.3
Soil (0–50)	74.8 (10.4)		66.2 (16.3)	
	NUE[d] (%)			
	49 (7.2)		38 (5.0))	
	^{15}N recovery[e] (%)			
	96		79	

[a]Maize-**wheat**-common bean-barley. [b]Maize-**wheat**-red clover-red clover. [c]SD (n=4). [d]Nutrient uptake efficiency. [e]Plant+soil.

Nitrogen-15 values recovered by wheat plants in both treatments were in the range (30–57%) of results reported by other authors in Chile [25,26]. About 50% of ^{15}N was recovered in treatment T1W-Y2 and 38% in T3W-Y2. The former estimate was higher than those found by Pino et al. [25] for wheat when using sodium nitrate and ammonium nitrate as N sources, but lower than those found for urea. Total ^{15}N recovery (plant+soil) was considered high but, on average, similar to those reported by others [27]. Unaccounted-for ^{15}N amounts (losses) were low at 4 and 21% for treatments T1W-Y2 and T3W-Y2, respectively.

3.4. The fate of residue ^{15}N in soil and crop

The fate of ^{15}N in maize and wheat residues is shown in Figs. 1 and 2, respectively. Measurements for two following crops (wheat and red clover) are reported in the former (Experiment 1), and for one crop (bean) in the latter (Experiment 2).

After incorporation of labelled maize residues (TM2-Y2) the following wheat plants recovered 4% (1.63 kg ha^{-1}) of the ^{15}N and the next crop in the sequence (red clover) recovered approximately 0.5% (0.15 kg ha^{-1}). The N recovered by wheat was somewhat less than values reported by others using non-leguminous residues [14]. The very low recovery in red clover may partially be explained by biological N_2 fixation.

Total N recovery in the plant-soil system for Experiment 1 was slightly over 100% in both sequential crops: 116 and 119% for wheat and red clover respectively. These results are partially explained by high N retention in soil and suggest that most N has been immobilized and partially stabilized in SOM. Nitrogen contribution of decomposing labelled residues, low in N content and without N-addition to the next crop (wheat) is expected to be very low [14]. Due to biological N_2 fixation in red clover, soil N contribution is not relevant. However, our results suggest that some contamination could have occurred during sampling or handling soil samples for ^{15}N-analysis.

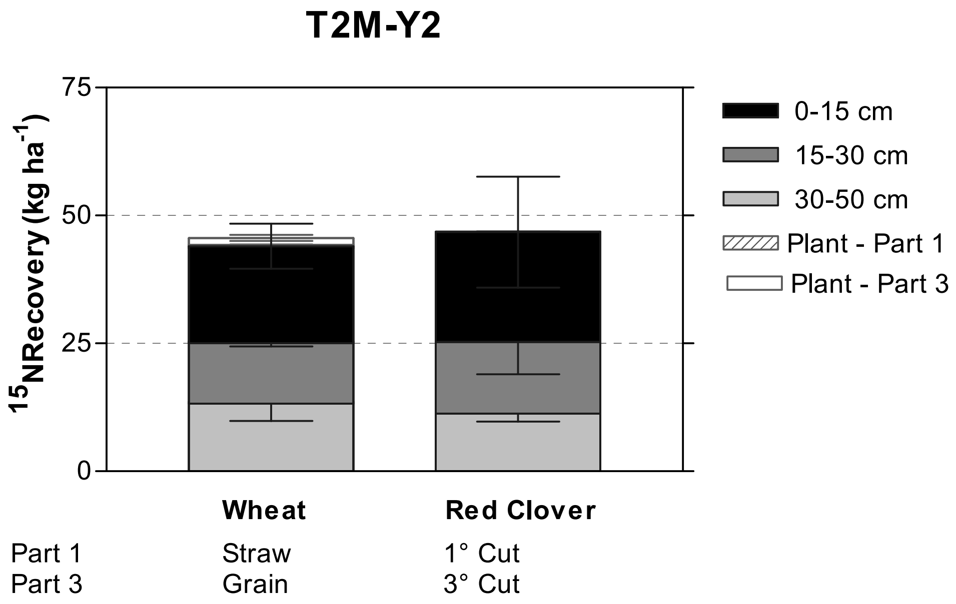

FIG. 1. The fate of ^{15}N-labelled maize residues in soil and crop.

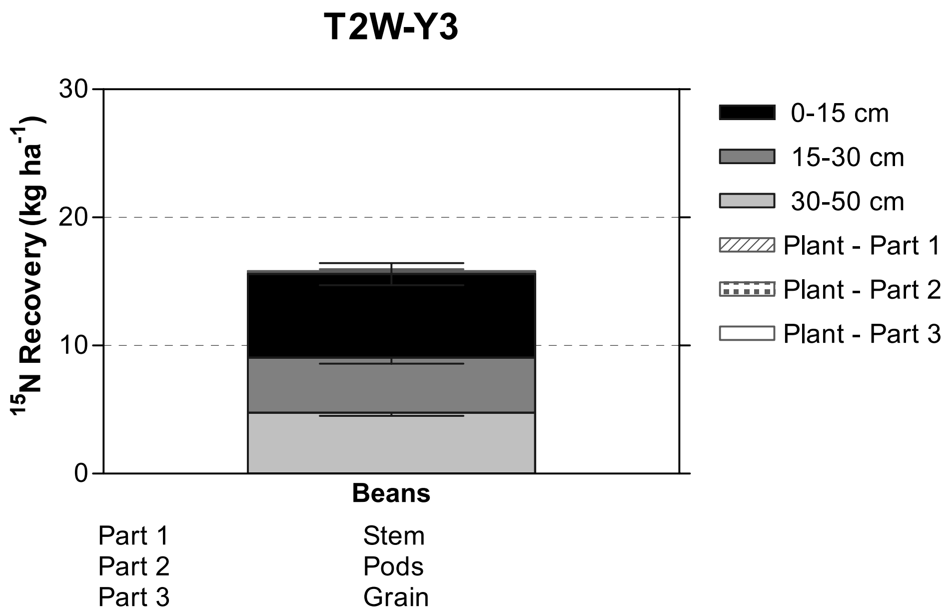

FIG. 2. The fate of ^{15}N-labelled wheat residues in soil and crop.

Results for Experiment 2 (use of labelled wheat residues, T2W-Y3) showed that N recovery by following bean plants was again low (0.228 kg ha^{-1}), representing 1.9% of the ^{15}N added as labelled residues. This recovery was lower than that estimated in following wheat from decomposing labelled maize residues. However, this result was expected since common bean is a legume and obtains N through biological fixation. Total N recovery in the plant-soil system in this treatment was similar to that reported for Experiment 1. There was a high N retention in soil, suggesting that most N had been immobilized and partially stabilized in SOM. Nitrogen contribution to the next crop (beans) from decomposing labelled wheat residues, low in N content and without N-addition, is expected to be very low [14]. As for red clover, soil N contribution is not relevant, since bean is an N_2-fixing crop. Nevertheless, total N recoveries in the plant-soil system over 100% suggest possible contamination during sampling or handling of soil samples for ^{15}N-analysis.

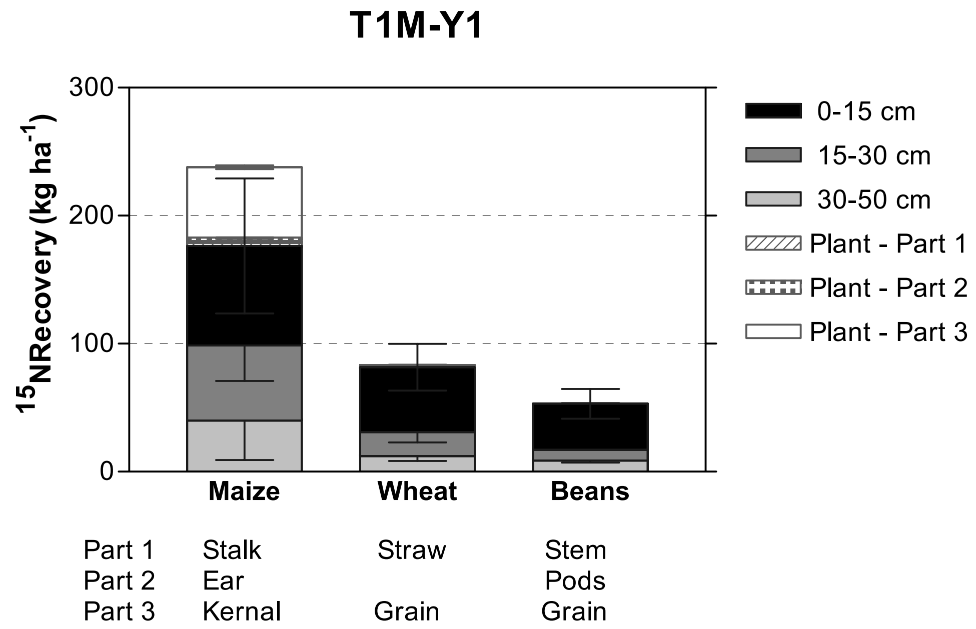

FIG. 3. The fate of ^{15}N-labelled fertilizer in soil and crop over three growing seasons in a rotation with incorporation of residues (Experiment 1).

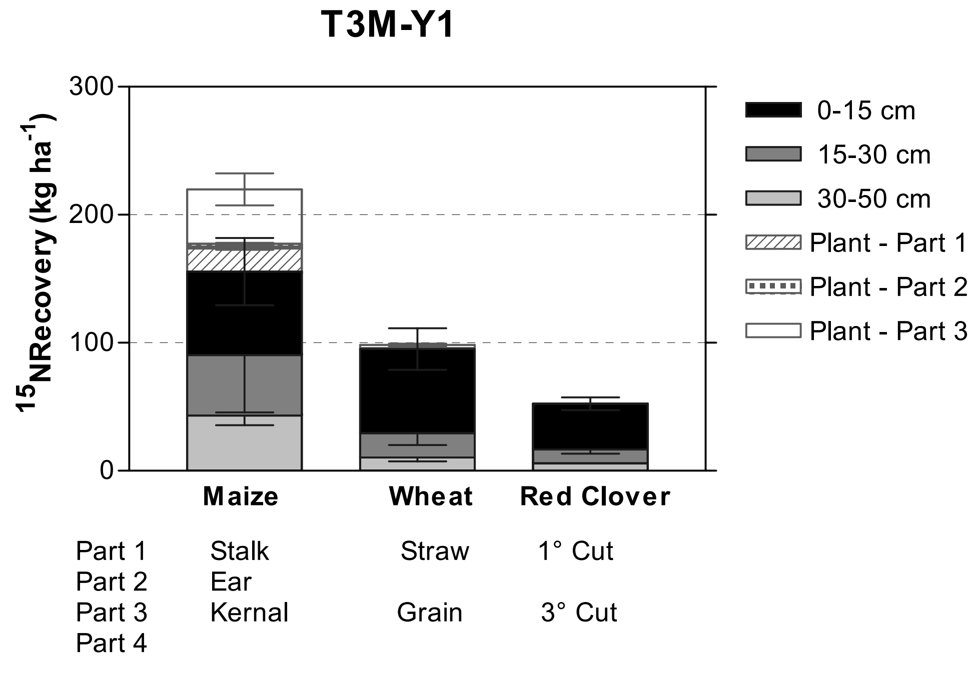

FIG. 4. The fate of ^{15}N-labelled fertilizer in soil and crop over three growing seasons in a rotation without incorporation of residues (Experiment 1).

3.5 The fate of ^{15}N-labelled fertilizer in soil and crop over three growing seasons in a rotation with and without incorporation of residues (Experiment 1)

Total N recovery in the plant-soil system over three growing seasons, T1M-Y1-maize-wheat-common bean and T3M-Y1-maize-wheat-red clover, are shown in Figs. 3 and 4, respectively. Total N recovery values after each growing season were 250, 83.5 and 53.4 kg ha^{-1} in the treatment incorporating residues (Fig. 3) for maize, wheat and beans, respectively. Corresponding amounts in the treatment without residues (Fig. 4) were 220, 98.4 and 52.5 kg ha^{-1}. Comparison between treatments (by growing season) showed that there were no significant differences in amounts of N recovered by the crops and retained in the soil (e.g. P=0.8320, P=0.4900, and P = 0.9901, for the first, second and third years, respectively). Total ^{15}N recovery at the end of the third growing season, i.e. ^{15}N in the soil plus ^{15}N recovered in the plant throughout the three growing seasons, did not show significant differences between treatments T1 and T3 (P=0.4516). Similarly, the combined comparison of N recovered by the crops and retained in the soil between T1 and T3 (i.e. considering the two first years both in Experiments 1 and 2), was not significant (P=0.6820).

Nitrogen recovered by the crop in both treatments was considerable only after one crop cycle (Figs. 3 and 4; Table X) and decreased with successive sequential crops.

Nitrogen retention in the soil in both treatments decreased in a rather similar way. These decreases were more than expected, suggesting that losses could have occurred between growing seasons. After one growing season, 59 and 52% of the fertilizer N added remained in the soil for T1M-Y1 and T3M-Y1, respectively. Corresponding amounts after two and three growing seasons were 28 and 18, and 33 and 18% respectively. Higher amounts retained in the soil after two sequential crops have been reported [14]. Major causes of loss were probably poor management or water (all crops were irrigated) causing runoff and leaching. Since there were no crops during winter, risks of losses existed. On the other hand, during early spring when mineralization increases rapidly due to favourable temperature and soil moisture, plants are small and a mineralization/plant-uptake asynchrony can occur, also causing leaching losses. Nitrogen losses by runoff could have occurred if inappropriate volumes of water were applied, especially with maize.

The ^{15}N enrichments both in the crop and the soil after the third sequential crop approached background levels (% excess values between 0.00014 and 0.00016). Due to the unconfined nature of the microplots, some mixing of the soil within and outside could have occurred during labour operations before sowing the third crop, thereby diluting the labelled N. For this reason, data on crop and soil recovery after the third sequential crop are not presented.

3.6. The fate of ^{15}N-labelled fertilizer in soil and crop during two growing seasons in a rotation with and without incorporation of residues (Experiment 2)

Total N recoveries in the plant-soil system over two growing seasons (T1W-Y2-wheat-beans and T3W-Y2-wheat-red clover) are shown in Figs. 5 and 6, respectively. Total N amounts recovered after two growing seasons were 203 and 176 kg ha^{-1} in treatments with and without residues, respectively. Comparison between treatments showed that, after two growing seasons, N recovered by the crop and retained in the soil was higher in treatment T1W-Y2 than estimates for T3W-Y2. However, the differences were small and not significant when compared by growing season (e.g. P=0.5272 and P=0.9901 for the first and second years, respectively) because of measurement variability, especially those for the soil. As in Experiment 1, total ^{15}N recovery at the end of the second growing season, ^{15}N in the soil plus ^{15}N recovered in the plant throughout the two growing seasons, did not show significant differences between treatments T1 and T3 (P=0.2776).

Nitrogen recovered by the crop in both treatments was important only after one crop cycle (Figs. 5 and 6, Table XII) and decreased with the following crop. These results are similar to those found in Experiment 1.

Nitrogen retention in the soil in both treatments decreased similarly. However, less N was retained in soil as compared to Experiment 1, mainly due to greater uptake by wheat than by maize. As in the former experiment, N losses occurred between growing seasons. Nevertheless, N-retention decrease in the soil was lower than in Experiment 1, after one growing season. In Experiment 2, 47 and 41% of the N-fertilizer remained in the soil for T1W-Y2 and T3W-Y2, respectively, after one crop cycle. Corresponding amounts after two growing seasons were 35 and 31%, respectively.

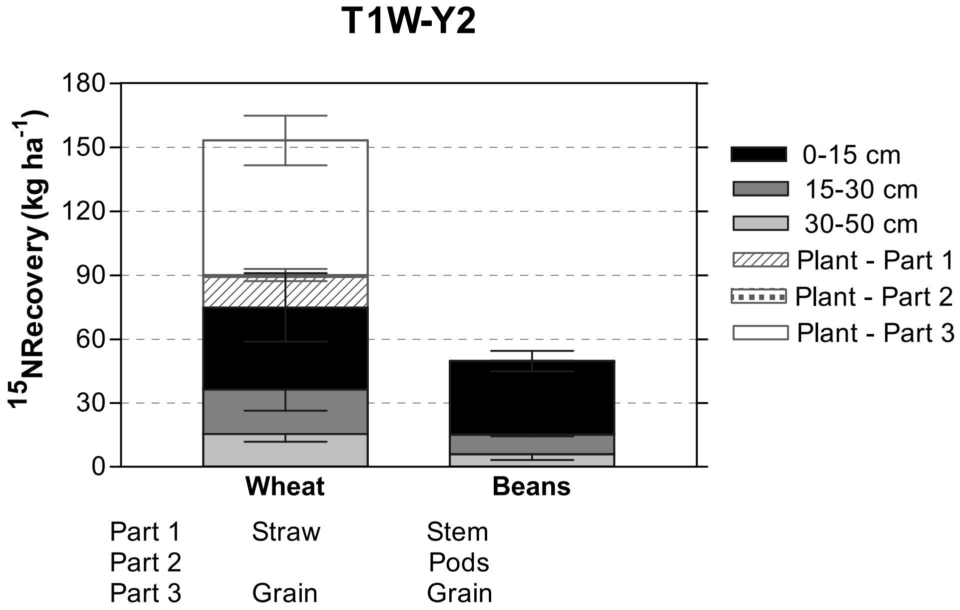

FIG. 5. The fate of ^{15}N-labelled fertilizer in soil and crop over two growing seasons in a rotation with incorporation of residues (Experiment 2).

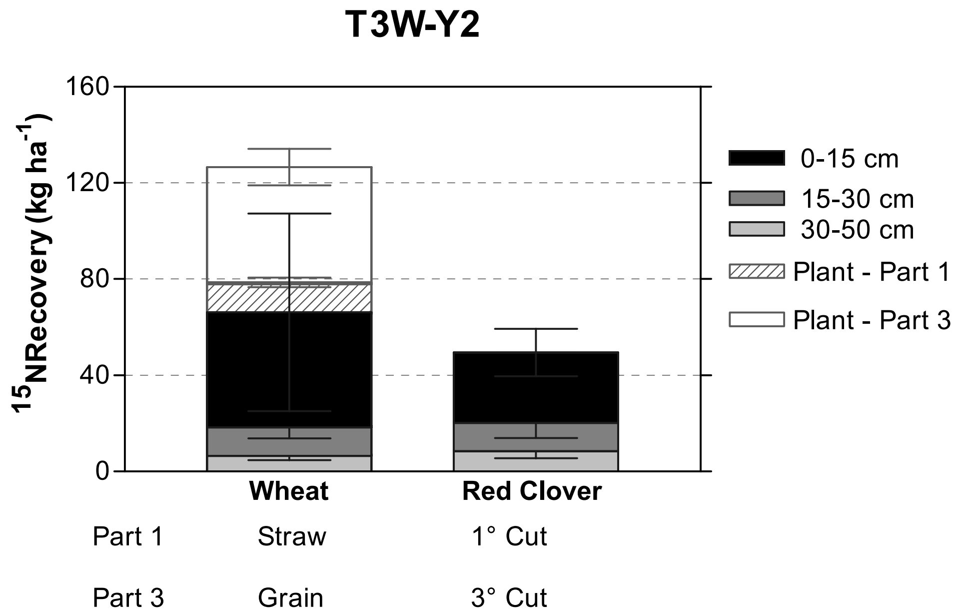

FIG. 6. The fate of ^{15}N-labelled fertilizer in soil and crop over two growing seasons in a rotation without incorporation of residues (Experiment 2).

The ^{15}N enrichment both in the crop and the soil after the second sequential crop, as in Experiment 1, approached background levels. As discussed above, this could have resulted from the unconfined nature of the microplots. However, the effect was unexpectedly more rapid than in the former experiment. For this reason, data on crop and soil recovery after the second sequential crop are not presented.

Our results from both experiments showed similar trends and did not support the hypothesis that increased inputs of C lead to increased retention of N in the system. Possible explanations can be found in that microplots were superimposed into a main experiment that was only 4 years old. Apparently, much more time is needed to test such a hypothesis since SOM changes occur gradually. On the other hand, the few data available from this study did not allow a secure comparison in the long run of total N recovery between treatments T1 and T2 versus T3, since it can be argued that T1 presented belowground recovery and T2 presented aboveground recovery. Considering that after one growing season almost all N from T2 remained in the soil (Figs. 1 and 2), in the long term one could expect an increase in N retention in the system incorporating residues. The relevance of this process would at the same time depend on the N added by the residues and the type of sequential crops in the rotation (e.g. legume versus non-legume). Furthermore, this comparison would also suggest lower labelled soil-N decreases and distinct N-stabilization levels than those shown for treatments T1 and T3 over time.

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