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Effects of ^{15}N-labelled crop residues and management practices on subsequent winter wheat yields, nitrogen benefits and recovery under field conditions

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SUMMARY

Nitrogen-15 enriched ammonium sulphate was applied to micro-plots in a field in which two leguminous (white clover and peas) and two non-leguminous (ryegrass and winter wheat) crops were grown to produce ^{15}N-labelled crop residues and roots during 1993/94. Nitrogen benefits and recovery of crop residue-N, root-N and residual fertilizer-N by three succeeding winter wheat crops were studied. Each crop residue was subjected to four different residue management treatments (ploughed, rotary hoed, mulched or burned) before the first sequential wheat crop (1994/95) was sown, followed by the second (1995/96) and third wheat crops (1996/97), in each of which residues of the previous wheat crop were removed and all plots were ploughed uniformly before sowing. Grain yields of the first sequential wheat crop followed the order: white clover > peas > ryegrass > wheat. The mulched treatment produced significantly lower grain yield than those of other treatments. In the first sequential wheat crop, leguminous and non-leguminous residues supplied between 29–57% and 6–10% of wheat N accumulated respectively and these decreased with successive sequential crops. Rotary hoed treatment reduced N benefits of white clover residue-N while no significant differences in N benefits occurred between residue management treatments in non-leguminous residues. On average, the first wheat crop recovered between 29–37% of leguminous and 11–13% of non-leguminous crop residues-N. Corresponding values for root plus residual fertilizer-N were between 5–19% and 2–3%, respectively. Management treatments produced similar effects to those of N benefits. On average, between 5 to 8% of crop residue-N plus root and residual fertilizer-N was recovered by each of the second and third sequential wheat crops from leguminous residues compared to 2 to 4% from non-leguminous residues. The N recoveries tended to be higher under mulched treatments especially under leguminous than non-leguminous residues for the second sequential wheat crop but were variable for the third sequential wheat crop. Relatively higher proportions of leguminous residue-N were unaccounted in ploughed and rotary hoed treatments compared with those of mulched and burned treatments. In non-leguminous residue-N, higher unaccounted residue-N occurred under burned (33–44%) compared with other treatments (20–27%).

INTRODUCTION

Nitrogen is the most limiting and commonly applied nutrient for crop production. The development of nutrient-responsive cultivars during the past few decades has led to an intensive use of N fertilizers. Both environment and economic problems associated with such practices have, however, led to a renewed interest in alternative management systems, including the substitution of chemical fertilizers with manures, composts and crop residues. The proper recycling of crop/pasture residues has therefore become important in maintaining or improving the fertility of soils (Parr *et al.* 1990; Goh & Williams 1999; Kumar & Goh 2000). In Canterbury, New Zealand most arable farmers normally burn their crop residues (Nguyen *et*

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al. 1995) before sowing the next crop. However, there is now increasing pressure to find alternative and efficient methods of residue management other than burning.

It is generally believed that when short-term pastures are ploughed-in, a large amount of N becomes available to the following crop and hence in the first year after ploughing-in of a grass/clover pasture, fertilizer N is generally not required to achieve optimum yields of wheat (Stephen 1982). In addition, the amount of soil N mineralized can be considerably greater than that required by a wheat crop and leaching losses in the first year can be substantial (Francis *et al.* 1995).

However, it is not known how much of the N mineralized following the ploughing-in of short-term pastures or leguminous and non-leguminous residues is derived from the decomposition of these residues and/or from the mineralization of soil organic N. Recently, it has been possible to quantify the N benefit of leguminous and non-leguminous residues based on ^{15}N uptake by a subsequent crop from ^{15}N-labelled residues (Francis *et al.* 1992; Haynes 1997).

Although experiments in New Zealand showed that grass/clover pasture residues generally contain 2–3% N and a C/N ratio low enough for net mineralization to occur during decomposition and the N incorporated in pasture residues may be as high as 200 kg N/ha (Francis *et al.* 1992), only 10% of the residue-N was recovered by a first-year wheat crop (Haynes 1997). However, recoveries as high as 40% have been reported from a greenhouse pot study (Williams & Haynes 1997).

In other studies elsewhere, where leguminous residues were incorporated into soils, the following cereal crops generally recovered between 10 to 34% of the leguminous residue-N (Ladd & Amato 1986; Hesterman *et al.* 1987; Müller & Sundman 1988; Sisworo *et al.* 1990; Bremner & Kessel 1992; Jensen 1996; Ranells & Wagger 1997). In comparison, between 3–20% of non-leguminous residue-N was recovered by subsequent crops in the first year (Vigil *et al.* 1991; Bremner & Kessel 1992; Thomsen & Jensen 1994; Jensen 1996; Jordan *et al.* 1996). In the second crop, in general, less than 5% was recovered from both leguminous and non-leguminous residues (Ladd & Amato 1986; Ta & Faris 1990; Vigil *et al.* 1991; Jensen 1996; Haynes 1997).

In many of these studies, the ^{15}N-labelled crop residues were raised elsewhere in pots or solution cultures for a short duration and then chopped into small pieces before being mixed with the sieved soil in cylinders and pushed into the soil in the field described as micro-plots. There have not been many reported studies on the recovery of crop residue-N under different field management practices of crop residues raised *in situ*.

The main objective of this study was to investigate wheat yields, N benefits and recovery by three successive wheat crops of N originating from ^{15}N-labelled leguminous and non-leguminous residues grown for seed in the field and subjected to four residue management treatments (ploughed, rotary hoed, mulched or burned).

MATERIALS AND METHODS

The field experiments were conducted at the Henley Research Farm of Lincoln University in the Canterbury region (43°29′ S, 172°27′ E) of New Zealand. The site is at an altitude of 50 m a.s.l. and has a temperate climate with mean temperature varying from 6·4 °C to 16·6 °C and a mean rainfall of 680 mm which is relatively evenly distributed throughout the year (Francis *et al.* 1995). The soil at the site is a Templeton silt loam (*Udic Ustochrept*). Prior to the commencement of present experiments, the paddock had Italian ryegrass grown for one year, which was ploughed-in in January 1993.

Present experiments began in February 1993 and continued until 1997. In the first year experiments (1993/94) two leguminous (white clover, *Trifolium repens* L. and field peas, *Pisum sativum* L.), and two non-leguminous (perennial ryegrass, *Lolium perenne* L. and winter wheat, *Triticum aestivum* L.) crops were grown for seed. After harvesting the grain, the residues of these crops were managed in four different ways in the second year experiments (1994/95) and a test crop of winter wheat was grown. During the 1995/96 and 1996/97 periods (namely, third and fourth year field experiments) a winter wheat crop was grown each year to determine the residual effects of treatments in the second year (1994/95) field experiments. A brief detail of the time plan and stages of field experiments is presented in Fig. 1.

First year field experiments (1993/94)

Four crops, namely white clover, peas, ryegrass and wheat were grown from seeds in 24 main plots (each 35×20 m^2) arranged in a randomized complete block design with six replicates. Wheat cv. Monarch, ryegrass cv. Moata, white clover cv. Kopu and peas cv. Whero were sown at a seed rate of 130, 30, 3 and 170 kg/ha, respectively. White clover and ryegrass crops were sown in the first fortnight of March 1993 while peas and wheat in the first fortnight of June 1993. All crops were fertilized with 200 kg/ha of single superphosphate. Results of MAF-Quick tests of the soil from the experimental site showed that soil pH and concentrations of extractable Ca, Mg and K were not limiting (Cornforth & Sinclair 1984).

In each main plot, five randomly placed micro-plots (1×1 m^2) were sited to which ^{15}N-labelled fertilizer was added as described below. Each of these

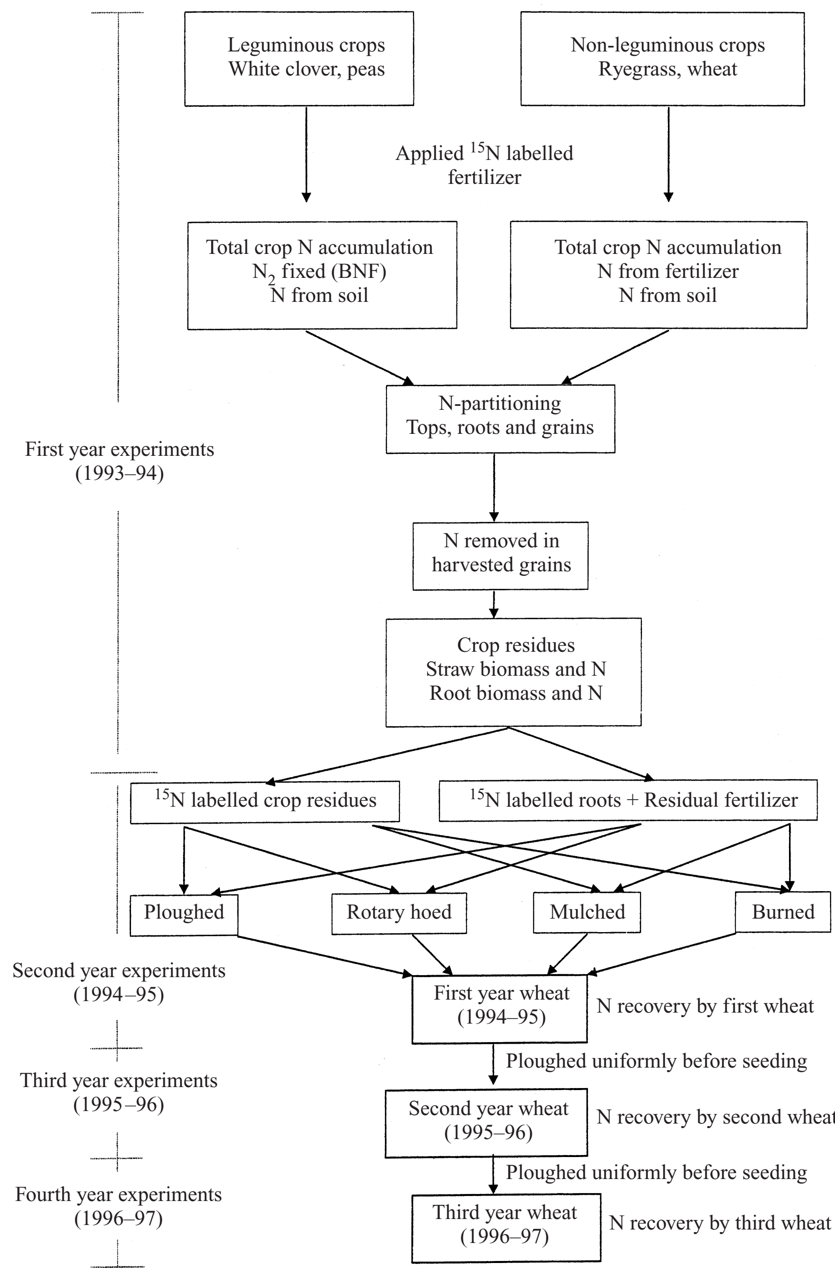

Fig. 1. Details of time plan and stages of field experiments from 1993 to 1997.

micro-plots was surrounded by an outside boundary plot (2×2 m^2). A total of 120 micro-plots were established. One of the five micro-plots per main plot was used for destructive sampling of soil and plants for analysis of dry matter yield (DMY) of tops and roots, N concentration and ^{15}N enrichment while the other four micro-plots were kept as non-destructive micro-plots (designated as micro-plots-A), each of which received one of the four crop residue treatments applied in the second year (1994/95) field experiments (Fig. 1).

White clover and peas received 30 atom % excess ^{15}N-enriched ammonium sulphate applied at 3·65 kg N/ha (as a tracer) on 18 June 1993 and 22 August 1993, respectively, once these crops were established. The wheat crop received 5 atom % excess

^{15}N-enriched ammonium sulphate fertilizer in two split applications (i.e. 100 kg N/ha before stem elongation and 20 kg N/ha before anthesis) while the ryegrass crop received the same fertilizer in two split applications (30 kg N/ha in mid-September and 30 kg N/ha, 3 weeks later).

Each of the 120 micro-plots received the ^{15}N-labelled ammonium sulphate while the boundary plots received unlabelled ammonium sulphate applied at the same rate of N as described by Goh *et al.* (1996).

As these micro-plots were not enclosed by walls, mixing of ^{15}N-labelled and unlabelled fertilizer may occur but this is minimized by taking the soil and plant samples as far as practicable from the middle of each micro-plot and not from the boundary between micro-plot and boundary plots. In the case of peas, wheat and ryegrass, there were six rows of plants per micro-plot and plant sampling was conducted from the middle four rows. With white clover, only two rows were seeded in the middle of each micro-plot and used for sampling.

The main plots received the same amount of N using unlabelled ammonium sulphate fertilizer applied within 1 or 2 days after the ^{15}N-fertilizer applications. The application of N fertilizer to wheat and ryegrass crops was designed to represent normal farm practice. The experimental site was kept free from diseases and pests using a preventive spray programme.

Crop and soil samples were taken at crop maturity from six random positions (using a 450 × 150 mm quadrat) in each main plot. The aboveground material was cut near to the soil surface using hand clippers and collected for processing and analyses. For the determination of ^{15}N and N concentration, plant top and root samples (200 × 150 mm quadrat) were obtained from the central area of the micro-plot reserved for destructive sampling in each main plot. A core sampling method was used for sampling roots. For white clover, stolons were taken as part of tops not roots. Root core samples were taken from two positions; one on the plant row and the other in between two plant rows using a steel tube (70 mm inner diameter) to a depth of 400 mm. Six cores per position were taken from each plot and bulked. The cores were placed on 70 mesh nylon sieves and washed with distilled water (Kumar *et al.* 1993).

At the final harvest, plants in the four micro-plots in each main plot were harvested using hand clippers. After removing the grains (or seeds), the crop residues were chopped into 50–60 mm long pieces before returning to the respective micro-plots. At final harvest, the main plots were machine harvested for grain (or seeds) and crop residues left in the field.

Soil samples for ^{15}N analyses were taken at four soil depths (0–50, 50–100, 100–200, 200–400 mm) from the micro-plots reserved for destructive sampling at final harvest only (one core per depth per plot).

Second year field experiment (*1994/95*)

This represents a continuation of first year field experiment and it was laid out as a split plot design. The four crop residues from the first year field experiment, namely white clover, peas, ryegrass and wheat retained in the main plots (each 35 × 20 m), were chopped using a mulching mower 2 to 3 weeks after harvest and spread as uniformly as possible as a surface mulch before applying the four different residue management treatments. Each of the main plots with crop residues established in 1993/94 was divided into four subplots (each 35 × 4 m). Each of these subplots in each of the crop residues contained one micro-plot (micro-plot-A) established during 1993/94 experiments to produce ^{15}N-labelled crop residues, roots and soil *in situ*. Before the application of residue management treatments in the second year field experiment (1994/95), an additional micro-plot (micro-plot-B) of the same dimensions as micro-plot-A was created in each of the subplots.

After the final harvest of each crop from first year experiments (1993/94), ^{15}N-labelled crop residues from all micro-plots-A (i.e. 24 micro-plots) for each kind of crop residue were collected, bulked, mixed, homogenized, weighed and subdivided into 24 equal portions (4 residue treatments × 6 replicates), each containing 1000 g for white clover, 900 g for peas, 900 g for ryegrass and 1300 g for wheat residues. The unlabelled crop residues from all 24 micro-plots-B were also treated similarly and divided in 24 equal lots as those for micro-plots-A. A small difference in weights of bulked labelled and unlabelled residues was adjusted using residues in appropriate main plots or micro-plots reserved for destructive sampling. The subdivided lots of residues were returned to the field but not to their respective micro-plots. Instead, each lot of subdivided labelled crop residues from micro-plots-A was applied to a micro-plot-B, while each micro-plot-A received a subdivided portion of unlabelled crop residues from micro-plot-B. The objective was to separate the effect of roots plus residual fertilizer from the aboveground crop residues. As a result of this exchange of crop residues, the micro-plots contained the following:

Micro-plots-A = unlabelled crop residues
+ labelled roots
+ labelled residual fertilizer *in situ* in soil

Micro-plots-B = labelled crop residues
+ unlabelled roots
+ unlabelled residual fertilizer *in situ* in soil

Each subplot including its micro-plot-A and micro-plot-B received one of the following crop residue management treatments: (i) ploughed, (ii) rotary hoed, (iii) mulched or (iv) burned on 9 May 1994. In the ploughed treatment, crop residues were buried to a depth of 150–200 mm using a mouldboard plough except for the area within the micro-plots and boundary plots which were later worked in by hand using a spade to simulate ploughing. A Howard rotavator was used in the rotary hoed treatment to mix the crop residue with the soil to a depth of 100–150 mm, while the area surrounding the micro-plots and boundary plots was rotavated with a small rotavator. In the mulched treatment, crop residues in both micro-plots and subplots were left undisturbed on the soil surface without further treatment. In the burned treatment, crop residues in subplots and also micro-plots were burned using a gas flame burner mounted on a tractor.

Crop residues were sampled before and after burning (using 0·5 m² quadrat) from 3 random spots in each subplot (one for each type of crop residue and six replicates) of burned treatment. All samples were dried in an oven at 60 °C for 48 h and dry weight determined. For estimating the amount of ash produced, a subsample from the crop residue materials collected after burning was washed with cold distilled water to wash off any ash adhering to the unburnt residues, dried in the oven as above and the loss in weight was taken as the amount of ash produced. Another subsample of crop residue materials collected after burning was placed on a 1 mm sieve and the ash was collected for chemical analysis.

Before sowing the first sequential wheat crop, soil samples (0–150 mm depth) were taken randomly from the whole experimental area and subjected to New Zealand "MAF-Quick-Test" analysis (Cornforth & Sinclair 1984). Results obtained (pH 5·7; Olsen P 19 and extractable S 15), showed that the soil nutrient status was satisfactory (Cornforth & Sinclair 1984) and hence no fertilizer P, S or N was applied to the wheat crop.

The ploughed and rotary hoed plots were disced and rolled to level the soil a day before sowing wheat (cv. Monad) on 25 May 1994. Direct seeding was carried out in mulched and burned plots. The wheat crop was sown in rows 150 mm apart at 130 kg/ha seed rate (adjusted to 97% germination) for achieving the target plant population of 250 plants/m².

At final harvest, plants were sampled from four random spots (each 1·0 m² quadrat) in a subplot for recording the final DMY, grain yield and yield parameters. Aboveground biomass was divided into harvestable grain and remaining straw and chaff, dried at 60 °C and weighed. Grain yield of wheat was adjusted to grain moisture content of 14%. Root samples were also obtained and the procedure for sampling, washing and cleaning of roots was described earlier. Wheat tops were also sampled from micro-plots-A and -B using the same procedures as described earlier for subplots. Soil samples from the micro-plots were taken only at the time of final harvest of wheat from four depths (0–50, 50–100, 100–200, 200–400 mm) using the methods as described earlier.

Third (1995/96) and fourth (1996/97) year field experiments

The first sequential wheat crop was machine harvested in January 1995. The crop residues left in the field were removed in March 1995 and all plots were ploughed, disced and rolled in May 1995 and a second crop of wheat (cv. Monad) was sown in June 1995. The areas within the micro-plots and boundary plots (*c.* 3×3 m²) were hand-worked with a spade to simulate ploughing. In 1996, after the harvest of the second wheat crop, the residues were removed and the field was prepared as in 1995 before the third wheat crop was sown but only three replicates were retained for this experiment.

Irrigation

From 1993 to 1996, the experimental plots were irrigated with sprinkler irrigation to bring the soil moisture content to field capacity when 50% of the available soil moisture was depleted. No irrigation was applied to the third sequential wheat crop (1996/97). The last irrigation was applied before anthesis or at peak flowering to each crop.

Preparation and analysis of soil and plant samples

Samples of tops, roots and grain (or seeds) of crops were dried at 60 °C for 48 h and ground through a Cyclotec 1092 sample mill. For ^{15}N analyses, soil samples were dried at 20 °C in forced draft cabinets for 72 h, sieved to pass through a 2 mm sieve then ground (< 250 μm) using a soil grinder (N.V. Tema) for one minute. Total N and C in soil, herbage, roots and grains, and ^{15}N enrichment were determined using a commercial continuous flow C-N analyser, connected to an isotope ratio mass spectrometer (Goh *et al.* 1996).

Definitions of terms used

Crop residues (CR) and crop residue-nitrogen (CR-N)

The CR refers to all aboveground crop and weed materials left in the field after the final harvest of the crops grown in first year field experiments (1993/94). The harvested material consisted mainly of grains (or seeds) of crops plus small amounts of straw and pods which were not returned to the field. The CR-N refers to the N content of crop residues.

Residual fertilizer-nitrogen (*RF-N*)

This refers to the amount of fertilizer-N applied in the first year field experiments (1993/94) that was retained in the soil after the harvest of crops.

Root-nitrogen (*RT-N*)

This refers to the N content of crop roots present at final harvest in the first year field experiments (1993/94).

Root-nitrogen plus residual fertilizer-nitrogen (*RTPRF-N*)

This refers to RT-N plus RF-N. It was assumed that amounts of RTPRF-N were similar in micro-plots-A and B, the only difference was that the RTPRF-N was ^{15}N-labelled in micro-plots-A and unlabelled in micro-plots-B.

Wheat crop nitrogen

This refers to wheat tops N + wheat grain N + weeds N present in a wheat crop.

Methods of calculations

Total and per cent nitrogen benefit (*NB*, *% NB*), *and nitrogen recovery from crop residues and from root-nitrogen plus residual fertilizer-nitrogen*

The formulas given by Ta & Faris (1990) were used for these estimates. The N benefit (NB, g N/m^2) represents the total N in the wheat crop originating from labelled CR-N and RTPRF-N of residues of white clover, peas, ryegrass or wheat calculated as:

$$NB = \frac{\text{T-}^{15}\text{N wheat}}{^{15}\text{N atom \% excess in CR-N (or RTPRF-N)}} \quad (1)$$

where T-^{15}N (total ^{15}N excess in wheat, g ^{15}N/m^2) = ^{15}N atom% excess of wheat × total N yield of wheat (g/m^2). For calculating the NB for each plant component, the ^{15}N atom% excess for each component (e.g. wheat grain) and N uptake by the component was used in the calculations. The total NB for the crop is the sum of N in each of the components determined.

The per cent N benefit was expressed on the basis of total N yield of wheat (g/m^2) as:

$$\%NB = \frac{NB}{\text{T-N uptake by wheat crop}} \times 100 \quad (2)$$

Total %NB

$$= \frac{\text{NB from CR-N} + \text{NB from RTPRF-N}}{\text{T-N uptake by wheat crop}} \times 100 \quad (3)$$

The N recovery from CR-N (or RTPRF-N) was calculated as NB from CR-N (or RTPRF-N) per total N (g/m^2) in CR-N (or RTPRF-N) as:

N recovery

$$= \frac{\text{NB from CR-N (or RTPRF-N)}}{\text{CR-N (or RTPRF-N)}} \times 100 \ (\%) \quad (4)$$

Total N recovery

$$= \frac{\text{NB from CR-N} + \text{NB from RTPRF-N}}{\text{Total N added (CR-N} + \text{RTPRF-N)}} \times 100 \ (\%) \quad (5)$$

Statistical analyses

Data were analysed using the split plot technique for analysis of variance (ANOVA) using SAS-1989 (Statistical Analyses System Inc., Raleigh, NC, USA). For the data in graphs where interaction between residues and management was significant, an interaction S.E. bar is presented for the comparison of treatment effects.

RESULTS

Amount of labelled ^{15}-N present as crop residue-nitrogen and root-nitrogen plus residual fertilizer-nitrogen

Total amounts of N present as CR-N and RTPRF-N for different crop residues before residue management treatments were applied are shown in Table 1. Of this total N present, RTPRF-N was labelled with ^{15}N in micro-plots-A while CR-N was labelled in micro-plots-B. In general, CR-N constituted the major proportion of total N present (Table 1).

Effect of burning of crop residues on loss of residue nitrogen

Proportions of crop residues burned accounted for about 22, 49, 57 and 71% of the white clover, peas, ryegrass and wheat residues present respectively, before burning (Table 2). The incomplete burning of residues was due to the wet weather in April and May

Table 1. *Mean amounts of total labelled and unlabelled N* (*kg/ha*) *present in micro-plots as crop residue-N* (*CR-N*) *and root-N plus residual fertilizer-N* (*RTPRF-N*) *at the commencement of second year field experiments* (*1994/95*)

Crop residue	CR-N	RTPRF-N	Total (CR-N + RTPRF-N)
White clover	223·0	82·9	306
Peas	134·1	95·5	230
Ryegrass	64·3	51·7	116
Wheat	71·5	74·1	146

1994, not allowing the residues to dry sufficiently before being burned on 9 May 1994. The proportion of N lost during burning depended on the amount of residue N present originally and the extent and degree of burning. The N losses represented 15, 24, 14 and 32% of the original N in white clover, field peas, ryegrass and wheat residues, respectively (Table 2). Corresponding losses in terms of amount of N lost/t residues DM were 15·1, 7·6, 1·7 and 2·4 kg respectively. When expressed as a fraction of total soil N, these losses were small (0·9 to 3·0%).

Table 2. *Amounts of crop residues present before and after burning, amounts of ash produced, N concentration and content in ash and in residues before and after burning, amount of N lost due to burning as a proportion of crop residues N and as a proportion of total soil N (0–50 mm depth)*

	Amount of residues (g/m^2)			Amount of ash (g/m^2)	N concentration (%)		Residue N content (g/m^2)			N loss		
										Amount (g/m^2)	Proportions	
Crop residue	Before	After	Loss*		Residue	Ash	Before burning	After burning	Ash		(% residue-N)	(% total soil N)
White clover	1000	782	218	52·2	2·23	3·02	22·3	17·4	1·6	3·3	15	2·92
Peas	900	456	444	88·4	1·49	3·82	13·4	6·8	3·4	3·3	24	3·02
Ryegrass	900	385	515	164·2	0·72	1·62	6·4	2·8	2·7	0·9	14	0·82
Wheat	1300	378	922	187·1	0·55	1·48	7·2	2·1	2·8	2·3	32	2·09

* Estimated by difference.

Grain yield and total dry matter yield of three sequential wheat crops

Grain yields and DMY of three sequential wheat crops are presented in Table 3. In general, grain yield and DMY showed similar trends except for the first sequential wheat crop where interaction between crop residues and residue management treatments were significant for DMY. For the first sequential wheat crop, grain yield followed the order: white clover > peas > ryegrass > wheat. Among the residue management treatments, mulched treatment produced significantly lower grain yield. The mulched and rotary hoed treatments produced significantly lower DMY as compared with other treatments (Table 3). In the second sequential wheat crop, significantly lower grain yield was produced under wheat residues as compared with other residues. Among residue management treatments, mulched treatment produced significantly higher grain yield compared with other residue management treatments (Table 3). In the third sequential wheat crop, in general, grain yield and DMY were significantly higher under non-leguminous than leguminous residues with no significant effect of any of the residue management treatments applied in 1994/95 (Table 3).

Nitrogen benefit (total NB, % NB) to sequential wheat crops from crop residue-nitrogen and root-nitrogen plus residual fertilizer-nitrogen

Direct evidence of NB from CR-N and from RTPRF-N was obtained in the present study by the use of labelled ^{15}N crop residues (Fig. 2). Because different amounts of CR-N were added for different crop residues to micro-plots (Table 1), comparisons between crop residues were based on % NB. Per cent NB were higher from leguminous CR-N than non-leguminous CR-N for the first wheat crop (1994/95) sown immediately following the application of residue management treatments (Fig. 2). The % NB to first sequential wheat crop under white clover residues ranged from 31 to 59% which were significantly higher than 21·7 to 30·8% for corresponding treatments under peas residues and between 5–11% under non-leguminous (ryegrass and wheat) residues. Significant effects of residue management treatments

Table 3. *Grain yield* (g/m^2) *and total dry matter yield* (*DMY*) *of three sequential wheat crops as affected by different crop residues and their management*

	First sequential wheat		Second sequential wheat		Third sequential wheat	
	Grain yield	DMY	Grain yield	DMY	Grain yield	DMY
Crop residues (CR)						
White clover	657	1320	348	778	222	527
Peas	579	1270	340	760	251	632
Ryegrass	472	1009	332	761	357	953
Wheat	354	734	275	624	327	880
S.E. (D.F.)	22·6 (15)	41·5 (15)	15·3 (15)	37·2 (15)	34·5 (6)	73·7 (6)
Management treatments (M)						
Ploughed	577	1216	303	684	290	730
Rotary hoed	544	931	301	704	280	701
Mulched	426	1020	362	793	298	740
Burned	536	1165	329	743	289	820
S.E. (D.F.)	17·7 (54)	39·6 (54)	14·1 (54)	34·3 (54)	12·4 (18)	47·7 (18)
Interaction (CR × M) S.E. (D.F.)	ns	78·8 (54)	ns	ns	ns	ns
CV (%)	17	18	17	18	14	22

on % NB occurred under white clover and peas residues (Fig. 2). Under white clover residues, % NB of the first sequential wheat crop was significantly lower under rotary hoed than under other residue management treatments (Fig. 2). In the case of peas, % NB was significantly higher under mulched and burned as compared with ploughed and rotary hoed treatments.

The uptake of CR-N was highest in the first sequential wheat crop and declined in subsequent crops (Fig. 2). However, even in the second wheat crop, % NB values were substantial and significantly higher under leguminous than non-leguminous residues and were in the order of white clover (24·1 %) > peas (13·4 %) > ryegrass (2·5 %) = wheat (3·8 %). In the third sequential wheat crop, the order was white clover (12·2 %) = peas (10.9 %) > ryegrass (2·3 %) = wheat (3·5 %). As far as residue management treatments are concerned, mulched treatment provided significantly higher % NB from CR-N in the second sequential wheat crop, while, in general, ploughed and mulched treatments provided higher % NB for the third sequential wheat crop (Fig. 2).

Per cent NB from RTPRF-N were low compared to those of CR-N (Fig. 2). In general, % NB values were significantly higher under white clover RTPRF-N (5–9 %) than other crop residues (< 3·1 %) in all three sequential wheat crops and the differences declined progressively with time (Fig. 2). The % NB from non-leguminous RTPRF-N contributed less than 2 % of wheat crop-N in all the three sequential wheat crops. The effects of residue management treatments were similar to those of % NB from CR-N as presented above. Significantly lower values of % NB were obtained from RTPRF-N than from CR-N for all residue management treatments (Fig. 2).

In actual field cropping conditions, both CR-N and RTPRF-N generally contributed towards the N uptake of the wheat crop. Total % NB (i.e. % NB from CR-N + % NB from RTPRF-N) showed almost similar trends as % NB from CR-N (Fig. 2). On an average, total % NB represented 56, 29, 6 and 12 % of the first sequential wheat crop-N for white clover, peas, ryegrass and wheat CR-N + RTPRF-N, respectively. Total % NB declined for the second and third sequential wheat crops, even though leguminous CR-N + RTPRF-N constituted a significant proportion (12 to 32 %) of wheat crop-N during these years (Fig. 2). Effects of residue management on total % NB were similar to those as explained above for % NB from CR-N.

Recovery of crop residue-nitrogen and root-nitrogen plus residual fertilizer-nitrogen

Recovery by three sequential wheat crops

First sequential wheat crop (1994/95): Most of the N in the first sequential wheat crop (wheat tops + grain + weeds) which was derived from CR-N (Fig. 3*a*), RTPRF-N (Fig. 3*b*) and CR-N + RTPRF-N (Fig. 3*c*) was present in the grain. In general, proportions of N recovered in weeds were not significant except in white clover mulched treatment (Fig. 3). Significant interactions between crop residue and management treatments occurred in N recoveries by the first sequential wheat crop (Fig. 3*a*, *b*, *c*). On average, 37, 29, 11 and 13 % of CR-N from white clover, peas, ryegrass and wheat were recovered by the first wheat crop (1994/95) respectively (Fig. 3*a*). Corresponding recovery values for RTPRF-N were 19, 5, 2·2 and 2·8 % (Fig. 3*b*).

Considerably less N was recovered by sequential

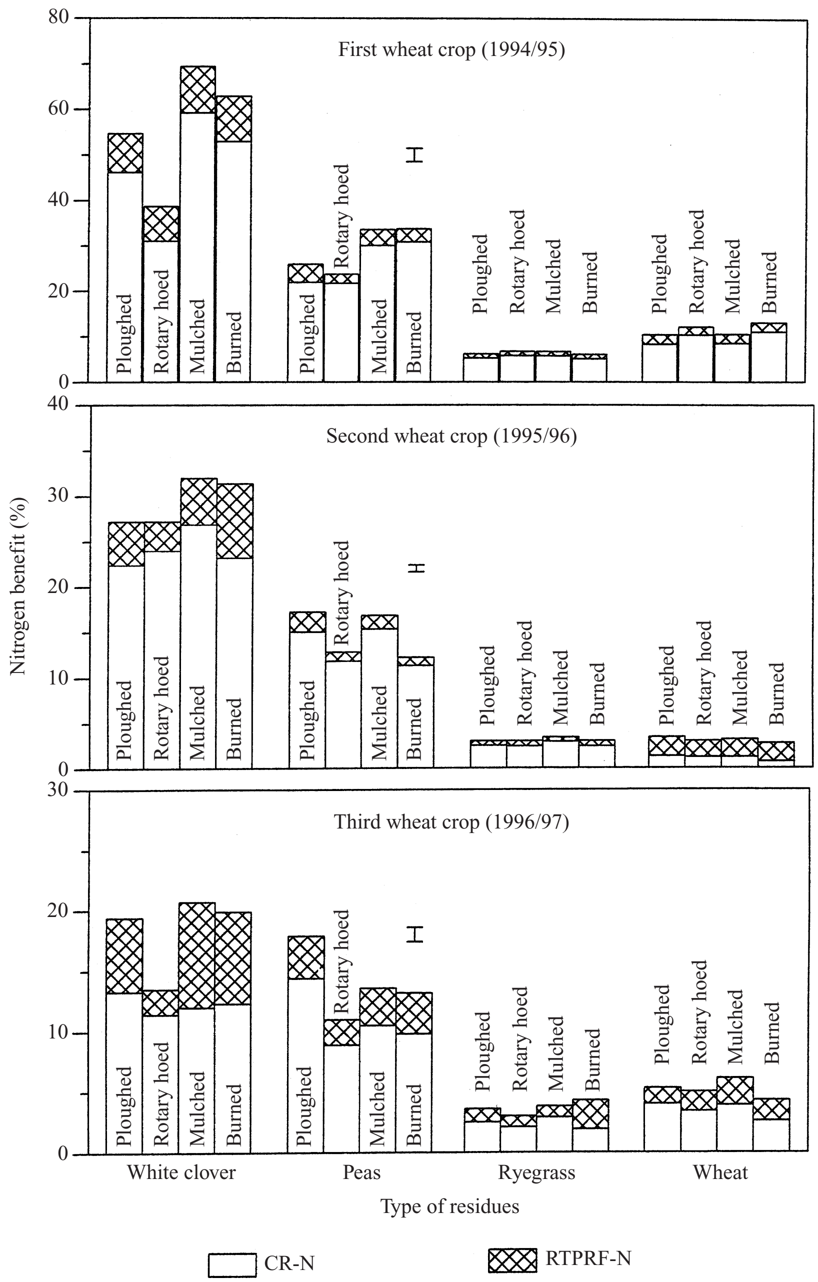

Fig. 2. Nitrogen benefit (%) from crop residue-N (CR-N), from root plus residual fertilizer-N (RTPRF-N) and from total (CR-N + RTPRF-N) to three sequential wheat crops under different crop residues and residue management treatments. Error bars represent S.E. (D.F. = 36 for first, second and 18 for third sequential wheat crops) of interaction between crop residues and residue management treatments.

wheat crops from RTPRF-N (Fig. 3*b*). Nonetheless, the recovery of RTPRF-N was significantly higher in white clover treatments (mean 19 %) than peas (mean 4 %) even though amounts of RTPRF-N of white clover and that of peas were similar (Table 1). Furthermore, N recovery from white clover RTPRF-N was significantly higher than those of non-leguminous residues.

In the present study, under field situations after crop harvest, both crop residues and roots were

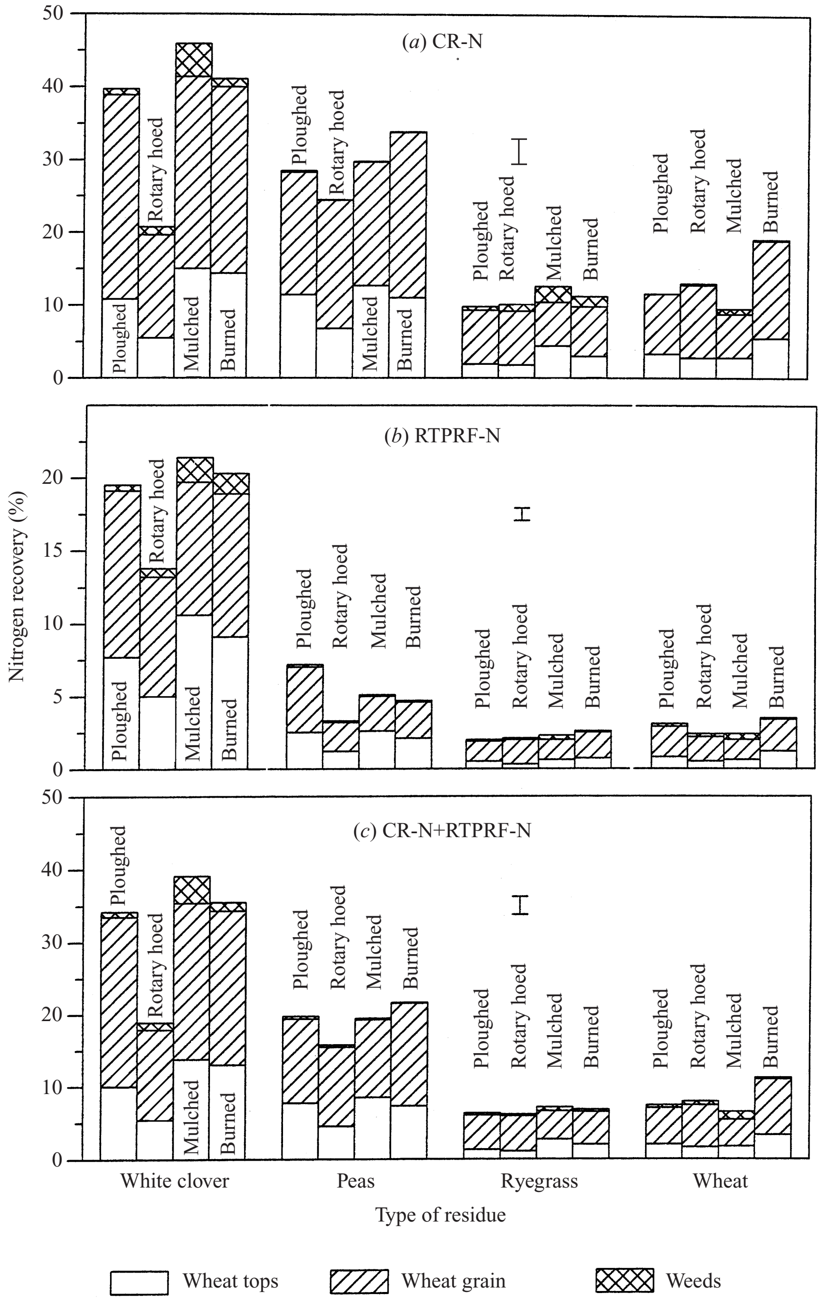

Fig. 3. Nitrogen recovery by the first wheat crop (1994/95) from (*a*) crop residue-N (CR-N), (*b*) root-N plus residual fertilizer-N (RTPRF-N) and (*c*) CR-N + RTPRF-N under different crop residues and residue management treatments. Error bars represent S.E. (D.F. = 36) of interaction between crop residues and residue management treatments.

present, total N recovery from CR-N and RTPRF-N was estimated together according to Eqn 6. The combined mean recovery values (Fig. 3*c*) were lower than those from CR-N alone (Fig. 3*a*) because combined values represented a weighted average of both CR-N and RTPRF-N. The amount of CR-N present was much higher than RTPRF-N (Table 1) but the recoveries of RTPRF-N were much lower

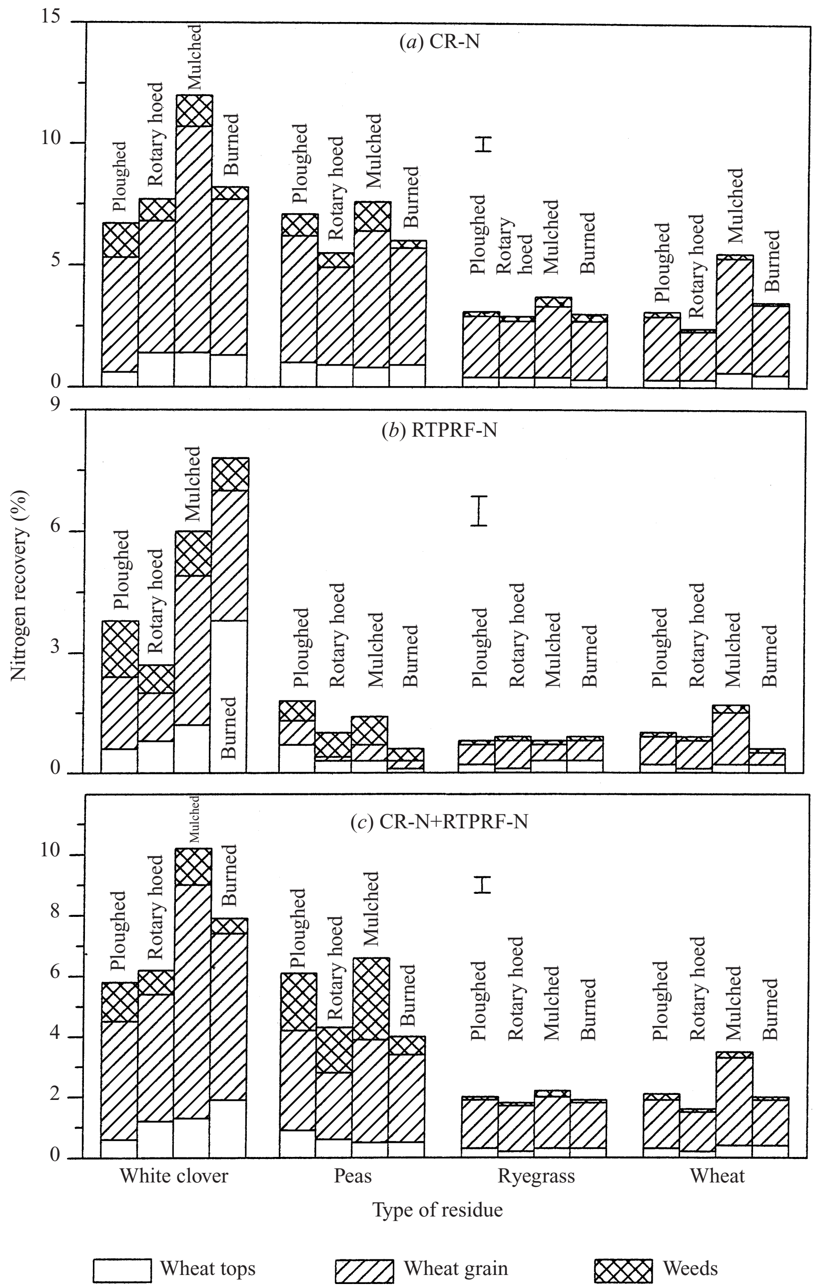

Fig. 4. Nitrogen recovery by the second wheat crop (1995/96) from (*a*) crop residue-N (CR-N), (*b*) root-N plus residual fertilizer-N (RTPRF-N) and (*c*) CR-N + RTPRF-N under different crop residues and residue management treatments. Error bars represent S.E. (D.F. = 36) of interaction between crop residues and residue management treatments.

than recoveries of CR-N by the sequential wheat crops.

There were no significant effects of residue management treatments on N recoveries by first sequential wheat from CR-N or RTPRF-N or CR-N + RTPRF-N (Fig. 3*a*, *b*, *c*) for non-leguminous crop residues. However, under leguminous residues, lower recoveries were found from the rotary hoed treatment compared to other treatments and were highly significant under white clover compared to other residues (Fig. 3*a*, *b*, *c*).

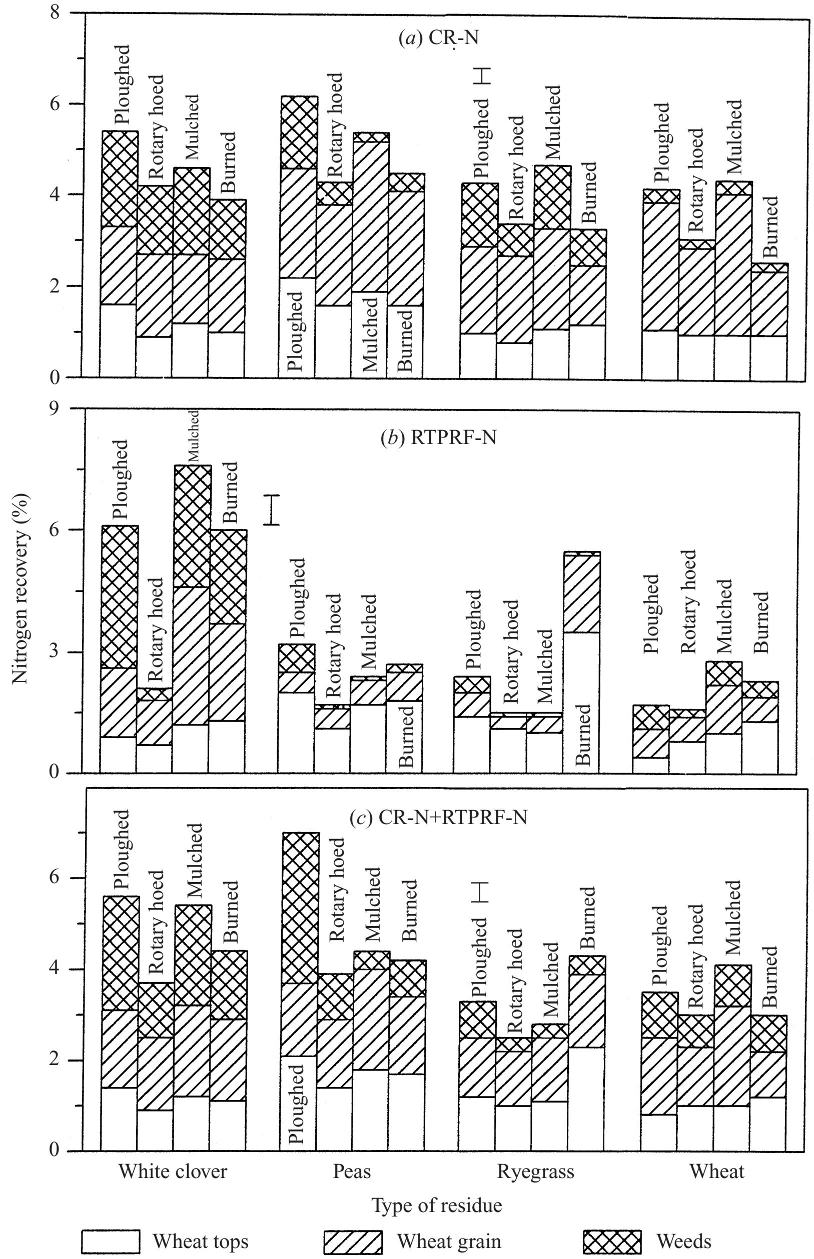

Fig. 5. Nitrogen recovery by the third wheat crop (1996/97) from (*a*) crop residue-N (CR-N), (*b*) root-N plus residual fertilizer-N (RTPRF-N) and (*c*) CR-N + RTPRF-N under different crop residues and residue management treatments. Error bars represent S.E. (D.F. = 18) of interaction between crop residues and residue management treatments.

Mean recoveries of N from CR-N + RTPRF-N under residue management treatments excluding rotary hoed were not significantly different (Fig. 3*a*, *b*, *c*).

Second (1995/96) and third (1996/97) sequential wheat crops: The N recoveries from CR-N, RTPRF-N and CR-N + RTPRF-N by the second (Fig. 4) and third (Fig. 5) sequential wheat crops were lower compared to those recovered by the first wheat crop (Fig. 3). Relatively higher N was recovered from CR-N than RTPRF-N by the second and third sequential wheat crops (Figs 4 and 5). Considerable CR-N and RTPRF-N was also recovered in weeds growing in

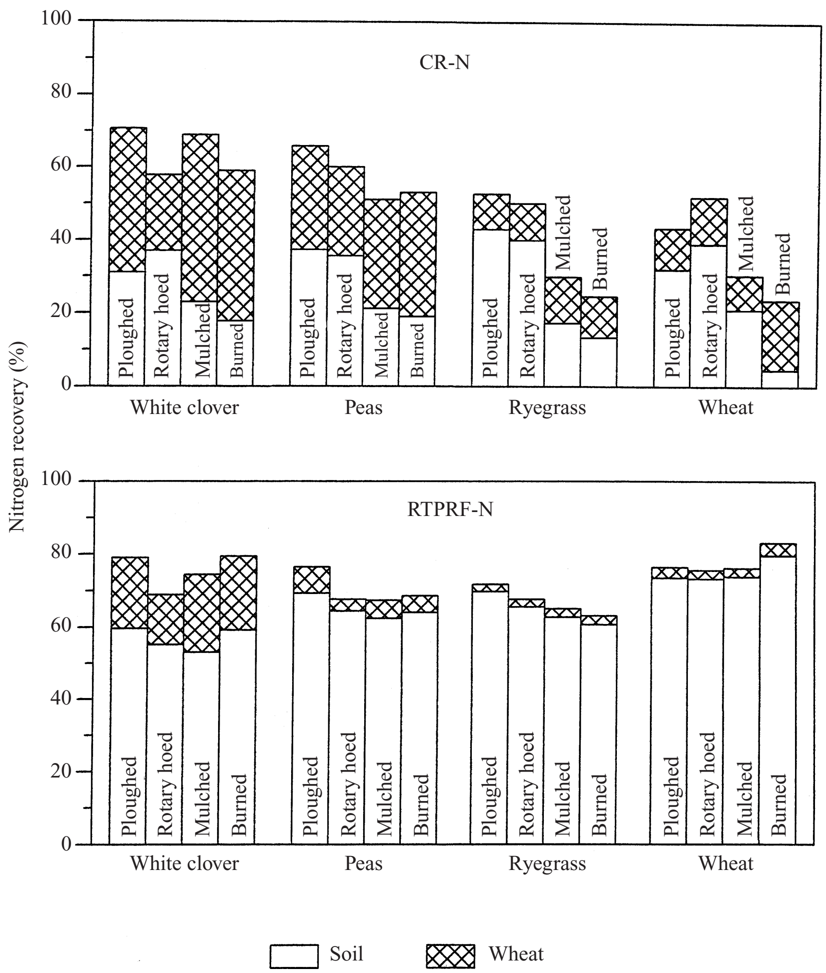

Fig. 6. Nitrogen recovery by the first wheat crop (1994/95) and N retained in soil from crop residue-N (CR-N) and from root-N plus residual fertilizer-N (RTPRF-N) at final harvest under different crop residues and residue management treatments.

second and third sequential wheat crops especially under leguminous residues (Figs 4 and 5). On average, between 5 to 8 % of CR-N + RTPRF-N was recovered by each of the second and third sequential wheat crops from leguminous residues compared to 2 to 4 % from non-leguminous residues (Figs 4 and 5). The N recoveries tended to be higher under mulched treatment especially under leguminous than non-leguminous residues for the second sequential wheat crop and were variable for the third sequential wheat crop.

Recovery in soil and estimated losses of nitrogen

Proportions of N recovered by the first sequential wheat crop (1994/95) and those retained in the soil as percentage of CR-N and RTPRF-N are shown in Fig. 6. In general, higher N was recovered in crop + soil from RTPRF-N compared to CR-N (Fig. 6). This was probably due to some of the undecomposed crop residues present in the field not being included in the analysis of the soil because materials larger than 2 mm were discarded when soil samples were sieved during preparation for N analysis. Between 20–25 % of the leguminous and 30–35 % of non-leguminous residues remained undecomposed in the field (data not reported). The N in these undecomposed residues was not determined. Thus no effort was made to estimate N losses (unaccounted N) after the first sequential wheat crop but after the second sequential wheat crop it was expected that most of the crop residues were decomposed and most of the residue-N was probably taken up by crops, lost or incorporated into soil N.

After the harvest of the second sequential wheat crop, in general, 58 to 67 % of the CR-N was

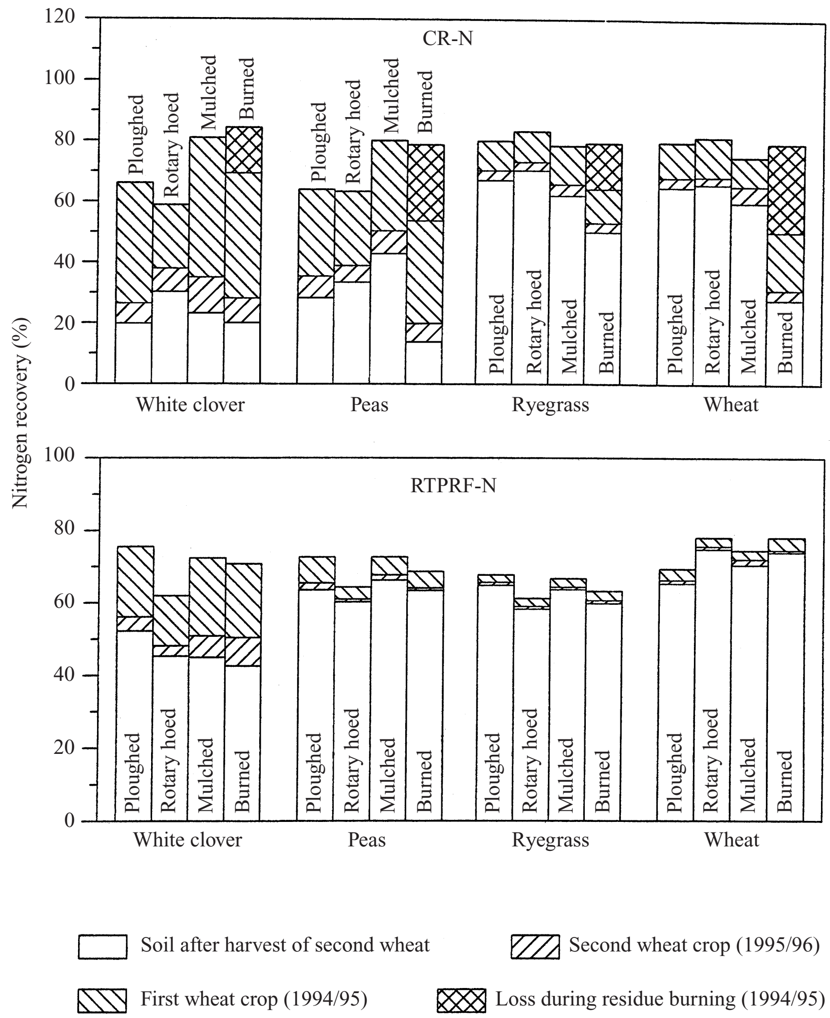

Fig. 7. Nitrogen recovered by the first wheat crop (1994/95), second wheat crop (1995/96) and N retained in soil after the harvest of second wheat crop from crop residue-N (CR-N) and from root-N plus residual fertilizer-N (RTPRF-N) and proportion of CR-N lost during burning (1994/95) in burned treatment under different crop residues and residue management treatments.

recovered (in two sequential wheat crops + soil) from leguminous residues under ploughed and rotary hoed treatments with the lowest recoveries occurring under rotary hoed treatment (Fig. 7). Significantly higher N was unaccounted for (33 to 42%) when leguminous residues were incorporated (ploughed and rotary hoed treatments) compared to those (20%) mulched and burned treatments after two subsequent wheat crops. For non-leguminous residues, no significant differences occurred between residue management treatments but the unaccounted N for CR-N (about 20%) were similar to those of mulched and burned treatments of leguminous residues.

There were no significant differences in total N recoveries from RTPRF-N (Fig. 7). About 70% of RTPRF-N was retained in the soil after two sequential wheat crops, thus leaving about 30% unaccounted for, which was probably lost from the system. Lower RTPRF-N recoveries also occurred under rotary hoed treatment than other residue management treatments especially under white clover residues. Comparatively, higher unaccounted RTPRF-N compared to that of CR-N occurred under non-leguminous residues in all treatments (Fig. 7).

The ^{15}N enrichment of both CR-N and RTPRF-N in the soil after the third sequential wheat crop (1996/97) was variable and reaching background levels (0·3669 to 0·37439 atom%). Due to the unconfined nature of the micro-plots, some mixing of the soil within and outside the micro-plots could have occurred during simulated ploughed operations carried out before sowing of the third wheat crop, thereby diluting the labelled-N in micro-plots. For this reason, data on CR-N and RTPRF-N recovered in the soil after the third sequential wheat crop were not presented.

DISCUSSION

Estimated amounts of N lost (9–33 kg N/ha) due to burning of white clover, field peas, ryegrass and wheat residues (Table 2) were well within the range of 7 to 42 kg N/ha reported elsewhere (Winteringham 1984; Hobbs *et al*. 1991; Ball-Coehlo *et al*. 1993). But in the present study only 20–40% of the leguminous residues could be burned due to wet weather; had those been completely burned, these losses could be higher. Haynes (1999) reported that between 10–15 kg N/ha was lost annually when wheat residues were burned in a site near the present study area. A wide range of values reported in the literature is probably due to different residues and different degree and extent of burning attained in different studies. This may not be the only N loss mechanism from crop residues as high N losses in the form of ammonia volatilization have been reported to occur after residue burning because alkaline ash left on the soil surface increases urease activity (Bacon & Freney 1989; Lee & Atkins 1994). In addition the nutrients which are left in ash are highly soluble in water and may be prone to leaching and run-off losses (Kumar & Goh 2000). However, when expressed as a fraction of total soil N, N losses were small (0·9 to 3·0%) although these may become significant, if crop residues are burned annually. Apart from nutrient loss, burning of crop residues causes pollution and deprives the soils of organic matter (Kumar & Goh 2000).

Significantly lower grain yield of wheat under non-leguminous than under leguminous residues was expected because of lower N additions through non-leguminous residues (Table 1). In addition, high C:N ratio residues have been shown to immobilize soil N and adversely affected the yields of following crops (Kumar & Goh 2000). The significantly lower grain yield and DMY obtained under mulched treatment especially under non-leguminous residues were probably due to the low number of plants per unit area (m^2) established under this treatment (Kumar 1998). Poor grain yields under no-tillage surface residues have been related to a number of factors such as difficulty in seeding through thick residue mulch (Staniforth 1982; Burgess *et al*. 1996), low seed zone temperatures under residue mulched (Burgess *et al*. 1996; Swanson & Wilhelm 1996) and biological effects such as diseases (Kirkegaard *et al*. 1994; Smiley *et al*. 1996). The immobilized soil N during the first and second sequential crops under non-leguminous residues may have been released during the third year resulting in higher yields of third sequential wheat crops under non-leguminous residues compared to that of leguminous residues (Table 3). It is known that the immobilized soil N is ultimately mineralized once the C:N ratio of decomposing residues declines to about 25:1 (Kumar & Goh 2000).

Results of this study showed that between one-quarter to one-half of the N in the first sequential wheat crop originated from CR-N+RTPRF-N of white clover and peas, respectively. The % NB declined progressively for the second and third sequential wheat crops although leguminous CR-N+RTPRF-N constituted a significant proportion (12–32%) of wheat crop N. According to Moore (1974), in a small addition of plant residues with high N concentration (such as legumes), the availability of N to succeeding plants can be expected to decline progressively with each growing season since plant residues decomposed mainly in the first year. In a similar study on barley, Ta & Faris (1990) found that during the first, second and third years following the application of alfalfa residues, % NB were 15, 6 and 5% of total N yield of barley, respectively. These results are lower than those obtained for white clover and peas residues in the present study. The main reasons being that only 2·5 t/ha of alfalfa residues were added to the soil by Ta & Faris (1990). These workers stated that if higher amounts of alfalfa residue, equivalent to those produced after one year in field were added, % NB values would have been 4–5 times higher. Contributions of non-leguminous CR-N+RTPRF-N to subsequent wheat crops are expected to be small owing to their slow decomposition, lower N concentration (higher C:N ratio) and immobilization of soil N (Kumar & Goh 2000).

Present results showed that % NB from RTPRF-N can be substantial especially from leguminous crops for the first sequential wheat crop. Thus, this should not be overlooked when planning N management of subsequent wheat crops.

Higher values of % NB obtained corresponded to higher recoveries of N from CR-N. Higher recoveries from leguminous than non-leguminous residues were expected owing to higher N concentration and lower C/N ratio of leguminous residues (Ladd & Amato 1986; Kumar & Goh 2000).

Significantly higher recoveries of CR-N compared to RTPRF-N were obtained in the first sequential wheat crop. This is probably due to the higher C:N ratio and higher cutin content of roots compared to aboveground crop residues. Bergersen *et al*. (1992) also reported considerably low soybean root-N recoveries compared to straw-N by a subsequent oats crop. Another reason for low recoveries of RTPRF-N was because RTPRF-N consisted of residual fertilizer, the recoveries of which are known to be very small (1–5%) due to most of this N being stabilized in organic forms in the soil (Ladd & Amato 1986; Haynes 1999; Kumar & Goh 2000).

Nitrogen recoveries of leguminous CR-N (29–37%) by the first subsequent sequential wheat crop found in this study were higher than those (10–34%) reported in the literature for experiments which added both aboveground residues and roots to the soil (Ladd & Amato 1986), probably due to the absence of root materials in the CR-N studied as N recoveries from roots are generally lower than those from plant tops (Bergersen *et al.* 1992). This is also supported by the results of the present study where recoveries of RTPRF-N by the first sequential wheat crops were significantly lower than recoveries of CR-N. Estimated recoveries (19–32%) from both aboveground plus *in situ* roots (as leguminous CR-N+RTPRF-N in the present study) were well within the reported range of 10–34% for added plant materials to soils (Ladd & Amato 1986; Ta & Faris 1990; Harris *et al.* 1994). A possible reason for relatively higher N recoveries at the low end (i.e. 19 *v.* 10%) in the present study was that the crop residues were raised and managed *in situ* wherein suitable microbial communities were already in action. Furthermore, most reported studies used dried and ground crop residues of varying maturity raised in sand cultures or at other sites and mixed with sieved soil and buried at various soil depths inside small cylinders pushed into the field soil (Ladd *et al.* 1981; Ladd & Amato 1986; Jensen 1996; Haynes 1997). These systems are much closer to the rotary hoed treatment in the present study and hence could have resulted in lower reported N recoveries. In these studies, 25 to 70% of leguminous N was found in the soil organic N pool (Ladd & Amato 1986; Müller & Sundman 1988; Haynes 1997) probably due to the lack of synchronization between N release and N uptake by crops (Haynes 1997) and also ANI (Jenkinson *et al.* 1985; Azam *et al.* 1993). In addition, the relatively small particle size (<5 mm) of residues used in most of these studies could have contributed to greater N immobilization and lower crop N uptake (Jensen 1994).

Since the recovery of leguminous-N by a succeeding crop depends on many factors (e.g. crop management, soil properties and uptake ability of succeeding crops), results are expected to differ from experiments at different sites. For example, Yaacob & Blair (1980) reported that the recovery of forage leguminous-N increased from 13 to 56% when the number of years the soil was previously cropped to the leguminous crops increased from 1 to 6. In contrast, N recovery of soybean-N averaged 15% and was not affected by previous cropping history. Higher N recoveries than that generally reported (10–34%) have been reported from the ploughing-in of lucerne (71%) in Southern Ontario, Canada (Bruulsema & Christie 1987), Minnesota in the United States (48%; Hesterman *et al.* 1987) and Canterbury, New Zealand (40%) from a greenhouse pot study (Williams & Haynes 1997). These reported results are expected to vary depending on whether ^{15}N labelling or difference methods were used to calculate the recoveries (Ta & Faris 1990). Nonetheless, these recoveries of leguminous-N were low in comparison with recoveries of added labelled-N from fertilizers by cereal crops which are often in the range of 45–80% (Ladd & Amato 1986; Powlson *et al.* 1986, 1992; Haynes 1999).

As expected recoveries of CR-N+RTPRF-N by subsequent sequential wheat crops were low for leguminous (5–8%) and non-leguminous (2–4%) CR-N+RTPRF-N but were well within the reported range of 5–20% (Powlson *et al.* 1985; Wagger *et al.* 1985; Ladd & Amato 1986; Thomsen & Jensen 1994).

Comparisons of N recoveries from crop residues subjected to different management treatments (mulched, burned, rotary hoed and ploughed) have not been reported. However, in the few reported studies comparing tillage systems, Varco *et al.* (1989) reported higher N recoveries of vetch ^{15}N by corn under conventional tillage systems compared to no-tillage systems. Wade & Sanchez (1983) found greater N removal by corn and grain yield when Kudzu [*Pueraria phaseoloides* (Roxb.) Benth.] residues were incorporated compared to being left on the soil surface as a mulch. Other studies showed little or no difference in corn yields between conventional tillage and no-tillage following a leguminous crop (Triplett *et al.* 1979; Flannery 1981).

The effect of tillage on the recovery of CR-N by a following crop would depend not only on soil type and environment (e.g. water supply) but also on residue quality and synchronization between CR-N release and crop N demand. A slow but synchronous release would lead to higher N recoveries by crops from crop residue-N (Myers *et al.* 1997). This may have happened in the present study since almost twice the amount of CR-N was recovered by the first wheat crop from white clover residues under ploughed, mulched and burned treatments compared to those of rotary hoed treatment (Fig. 3).

In Canterbury, winter wheat crop generally begins to take up N rapidly at the onset of spring (Scott *et al.* 1992) when increasing soil temperatures enhance the decomposition of crop residues and the release of N which probably synchronize with the N uptake demand of the wheat crop. It is hypothesized that CR-N mineralized rapidly under the rotary hoed treatment even at low temperatures of autumn and winter due to greater soil-crop residue contact and most of the CR-N released entered the soil organic N pool or part of this N was lost. Although labelled N in the soil organic pool was not determined periodically, data on CR-N recovered in the soil at final harvest of the first sequential wheat crop (1994/95) (Fig. 6) showed that a relatively higher amount of

CR-N was present in soil under rotary hoed treatment compared to other treatments, especially under white clover residues. Thus, there appears to be a lack of synchronization between N release and crop uptake.

Another possible reason for lower N recoveries by the wheat crop under the rotary hoed treatments could be due to greater inter-mixing of residues with the soil resulting in 'added N interaction' (ANI). This could have resulted in higher soil N uptake compared with those of other treatments as the first wheat crop showed 20% less N uptake under rotary hoed compared to that of the ploughed treatment and also 46% less CR-N and 3% higher soil-N compared to the ploughed treatment (data not presented). The ANI has been shown to reduce labelled fertilizer-N recoveries when fertilizers were mixed with the soil (Jenkinson *et al*. 1985; Azam *et al*. 1993). This could increase or decrease the recoveries of CR-N depending on the soil and kind of crop residues added.

Relatively higher proportions of leguminous CR-N (31–34%) were unaccounted for compared to that for non-leguminous (16–25%) residues after the second sequential wheat crop. The unaccounted leguminous CR-N in the present studies was well within the range reported in earlier studies (Ladd *et al*. 1983; Harris *et al*. 1994; Haynes 1997) and interestingly this proportion is also similar to the reported values for inorganic fertilizers applied (Kumar & Goh 2000). This unaccounted N may be lost from the system either via leaching or denitrification. The absence of synchronization between N mineralization and crop N uptake is the probable reason for these losses. In addition, higher proportions of leguminous CR-N were unaccounted for from treatments when these residues were incorporated (rotary hoed treatment of white clover, 34–41%) compared to mulched treatment (19–20%), while higher proportions of non-leguminous CR-N were either lost or unaccounted for under residue burned treatments (33–34% due to losses by burning of residues and unaccounted N) compared to other treatments (20–27%). Rotary hoed and ploughed treatments have not been compared for N losses and dynamics although in a recent experiment at Lincoln University, significantly higher N losses through gaseous loss pathways (almost twice) were found when grass herb leys were rotary hoed compared to ploughed (Van der Weerden *et al*. 1998).

Cumulative proportions of leguminous CR-N+RTPRF-N recovered by three subsequent sequential wheat crops (29–44%) were significantly higher than those of non-leguminous CR-N+RTPRF-N (12–14%). Higher proportions of non-leguminous CR-N+RTPRF-N were recovered in the soil (61–64%) compared to that of leguminous residues (29–42%). However, higher amounts of N derived from leguminous CR-N+RTPRF-N (9–9·8 g N/m^2) were retained in soil after the second sequential wheat crop compared with that of non-leguminous CR-N+RTPRF-N (7·1–9·4 g N/m^2). This was probably due to higher amounts of N present as leguminous CR-N+RTPRF-N (23·0–30·6 g N/m^2) than those of non-leguminous CR-N+RTPFR-N (11·6–14·6 g/m^2) before residue management treatments were applied in the second year field experiments (1994/95) for growing the first sequential wheat crop.

CONCLUSIONS

Results obtained from the present field experiments have practical implications for the farmers and the environmental managers who are concerned about whether farmers should burn or incorporate crop residues.

Based on the results obtained, the burning of both leguminous and non-leguminous crop residues is not advisable as this practice did not provide any added advantage in terms of grain yield or N benefits to subsequent wheat crops but causes pollution and greater nutrient losses. Since there were no significant differences between rotary hoeing and ploughing-in of non-leguminous residues in terms of yield, N benefits, recovery or losses, either of these treatments can be used to incorporate non-leguminous residues. Although rotary hoeing of leguminous residues produced comparable yields and resulted in similar N losses from the system compared to ploughing-in, it resulted in lower N benefits to the first sequential wheat crop especially under white clover residues. This suggests that leguminous crop residues should be ploughed-in. The lower N yields under mulching in the present study resulted from the lower plant populations established under this treatment for both leguminous and non-leguminous residues. Despite these, the mulched treatment achieved comparable N benefits and resulted in lowest N losses from the system and was instrumental in achieving significantly greater grain yields and N benefits in the second sequential wheat crop. If farmers have the proper machinery to seed through the thick residue mulch, the mulched treatment has the potential for providing greater grain yields, N benefits and reduced N losses apart from conserving soil moisture. Further research on these aspects are needed before any recommendations on residue management treatments can be made.

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REFERENCES

AZAM, F., SIMMONS, F. W. & MULVANEY, R. L. (1993). Mineralization of N from plant residues and its interaction with native soil N. *Soil Biology and Biochemistry* **25**, 1787–1792.

BACON, P. E. & FRENEY, J. R. (1989). Nitrogen loss from different tillage systems and the effect on cereal grain yield. *Fertilizer Research* **20**, 59–66.

BALL-COEHLO, B., TIESSEN, H., STEWART, J. W. B., SALCEDO, I. H. & SAMPAIO, E. V. S. B. (1993). Residue management effects on sugarcane yield and soil properties in north-eastern Brazil. *Agronomy Journal* **85**, 1004–1008.

BERGERSEN, F. J., TURNER, G. L., GAULT, R. R., PEOPLES, M. B., MORTHORPE, L. J. & BROCKWELL, J. (1992). Contributions of nitrogen in soybean crop residues to subsequent crops and to soils. *Australian Journal of Agricultural Research* **43**, 155–169.

BREMNER, E. & VAN KESSEL, C. (1992). Plant available nitrogen from lentil and wheat residues during a subsequent growing season. *Soil Science Society of America Journal* **56**, 1155–1160.

BRUULSEMA, T. W. & CHRISTIE, B. R. (1987). Nitrogen contribution to succeeding corn from alfalfa and red clover. *Agronomy Journal* **79**, 96–100.

BURGESS, M. M., MEHUYS, G. R. & MADRAMOOTOO, C. A. (1996). Tillage and crop residue effects on corn production in Quebec. *Agronomy Journal* **88**, 792–797.

CABRERA, M. L. & KISSEL, D. E. (1989). Review and simplification of calculations in ^{15}N tracer studies. *Fertiliser Research* **20**, 11–15.

CHRISTENSEN, B. T. (1986). Barley straw decomposition under field conditions: Effect of placement and initial nitrogen content on weight loss and nitrogen dynamics. *Soil Biology and Biochemistry* **18**, 523–529.

CORNFORTH, I. S. & SINCLAIR, A. G. (1984). *Fertiliser and Lime Recommendations for Pastures and Crops in New Zealand*. Wellington: Ministry of Agriculture and Fisheries.

FLANNERY R. L. (1981). Conventional vs. no-tillage corn silage production. *Better Crops Plant Food* **66**, 3–6. (Summer-Fall.)

FOX, R. H., MYERS, R. J. K. & VALLIS, I. (1990). The nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin, and N contents. *Plant and Soil* **129**, 251–259.

FRANCIS, G. S., HAYNES, R. J., SPARLING, G. P., ROSS, D. J. & WILLIAMS, P. H. (1992). Nitrogen mineralization, nitrate leaching and crop growth following cultivation of a temporary leguminous pasture in autumn and winter. *Fertiliser Research* **33**, 59–70.

FRANCIS, G. S., HAYNES, R. J. & WILLIAMS, P. H. (1995). Effects of the timing of ploughing in temporary leguminous pastures and two winter cover crops on nitrogen mineralization, nitrate leaching and spring wheat growth. *Journal of Agricultural Science, Cambridge* **124**, 1–9.

GOH K. M. WILLIAMS P. H (1999). Comparative nutrient budgets of temperate grazed pastures. In *Nutrient Disequilibria in Global Agroecosystems: Concepts and Case Studies* (Eds E. M. A. Smaling, O. Onema & L. O. Fresco), pp. 265–294. Wallingford: CAB International.

GOH, K. M., MANSUR, I., MEAD, D. J. & SWEET, G. B. (1996). Biological nitrogen fixing capacity and production of different understorey pastures in *Pinus radiata*-pasture agroforestry system in New Zealand. *Agroforestry Systems* **34**, 33–39.

HARRIS, G. H., HESTERMAN, O. B., PAUL, E. A., PETERS, S. E. & JANKE, R. R. (1994). Fate of legume and fertiliser nitrogen-15 in a long-term cropping system experiment. *Agronomy Journal* **86**, 910–915.

HAYNES, R. J. (1997). Fate and recovery of ^{15}N derived from grass/clover residues when incorporated into a soil and cropped with spring or winter wheat for two succeeding seasons. *Biology and Fertility of Soils* **25**, 130–135.

HAYNES, R. J. (1999). Fate and recovery of ^{15}N labelled fertilizer urea applied to winter wheat in spring in the Canterbury region of New Zealand. *Journal of Agricultural Science, Cambridge* **133**, 125–130.

HESTERMAN, O. B., RUSSELLE, M. P., SHEAFFER, C. C. & HEICHEL, G. H. (1987). Nitrogen utilization from fertilizer and legume residues in legume-corn rotations. *Agronomy Journal* **79**, 726–731.

HOBBS, N. T., SCHIMEL, D. S., OWENSBY, C. E. & OJIMA, D. S. (1991). Fire and grazing in the tall grass prairie: contingent effect on nitrogen budgets. *Ecology* **72**, 1347–1382.

JENKINSON, D. S., FOX, R. H. & RAYNER, J. H. (1985). Interactions between fertiliser nitrogen and soil nitrogen – The so-called "priming" effect. *Journal of Soil Science* **36**, 425–444.

JENSEN, E. S. (1994). Mineralisation-immobilisation of nitrogen in soil amended with low C:N ratio plant residues with different particle sizes. *Soil Biology and Biochemistry* **26**, 519–521.

JENSEN, E. S. (1996). Nitrogen acquisition by pea and barley and effects of their crop residues on available nitrogen for subsequent crops. *Biology and Fertility of Soils* **23**, 459–464.

JORDAN, D., BRUCE, R. R. & COLEMAN, D. C. (1996). Nitrogen availability to grain sorghum from organic and inorganic sources on sandy and clayey soil surfaces in a greenhouse pot study. *Biology and Fertility of Soils* **21**, 271–276.

KIRKEGAARD, J. A., ANGUS, J. F., GARDNER, R. A. & MULLER, W. (1994). Reduced growth and yield of wheat with conservation cropping. I. Field studies in the first year of the cropping phase. *Australian Journal of Agricultural Research* **45**, 511–528.

KUMAR, K. (1998). *Effects of different crop residues and management practices on soil nitrogen dynamics, yield and recovery of nitrogen by wheat*. Ph.D. thesis, Lincoln University, Canterbury: New Zealand.

KUMAR, K. & GOH, K. M. (2000). Crop residues and management: Effects on soil quality, soil nitrogen dynamics, crop yield and nitrogen recovery. *Advances in Agronomy* **68**, 198–320.

KUMAR, K., PRIHAR, S. S. & GAJRI, P. R. (1993). Determination of root distribution of wheat by auger sampling. *Plant and Soil* **149**, 245–253.

LADD, J. N. & AMATO, M. (1986). The fate of nitrogen from legume and fertilizer sources in soils successively cropped with winter wheat under field conditions. *Soil Biology and Biochemistry* **18**, 417–425.

LADD, J. N., AMATO, M. A., JACKSON, R. B. & BUTLER, J. H. A. (1983). Utilisation by wheat crops of nitrogen from legume residues decomposing in soils in the field. *Soil Biology and Biochemistry* **15**, 231–238.

Ladd, J. N., Oades, J. M. & Amato, M. (1981). Distribution and recovery of nitrogen from legume residue decomposing in soils sown to wheat in the field. *Soil Biology and Biochemistry* **13**, 251–256.

Lee, D. S. & Atkins, D. H. F. (1994). Atmospheric ammonia emissions from agricultural waste combustion. *Geophysical Research Letters* **21**, 281–284.

Moore, A. W. (1974). Availability to Rhodesgrass (*Chloris gayana*) of nitrogen in tops and roots added to soil. *Soil Biology and Biochemistry* **6**, 249–255.

Müller, M. M. & Sundman, V. (1988). The fate of nitrogen (^{15}N) released from different plant materials during decomposition under field conditions. *Plant and Soil* **105**, 133–139.

Myers, R. J. K., Noordwijk, M. V. & Vityakon, P. (1997). Synchrony of nutrient release and plant demand: plant litter quality, soil environment and farm management options. In *Driven by Nature: Plant Litter Quality and Decomposition* (Eds G. Cadisch & K. E. Giller), pp. 215–229. Wallingford: CAB International.

Nguyen, M. L., Haynes, R. J. & Goh, K. M. (1995). Nutrient budgets and status in three pairs of conventional and alternative mixed cropping farms in Canterbury, New Zealand. *Agriculture Ecosystems and Environment* **52**, 149–162.

Parr, J. F., Stewart, B. A., Hornick, S. B. & Singh, R. P. (1990). Improving the sustainability of dryland farming systems: A global perspective. In *Advances in Soil Science Vol. 13: Dryland Agriculture: Strategies for Sustainability* (Eds R. P. Singh. J. F. Parr & B. A. Stewart), pp. 1–8. New York: Springer-Verlag.

Powlson, D. S., Jenkinson, D. S., Pruden, G. & Johnston, A. E. (1985). The effects of straw incorporation on the uptake of nitrogen by winter wheat. *Journal of Science Food and Agriculture* **36**, 26–30.

Powlson, D. S., Pruden, G., Johnston, A. E. & Jenkinson, D. S. (1986). The nitrogen cycle in the Broadbalk wheat experiment: recovery and losses of ^{15}N-labelled fertiliser applied in spring and inputs of nitrogen from the atmosphere. *Journal of Agricultural Science*, *Cambridge* **107**, 591–609.

Powlson, D. S., Hart, P. B. S., Poulton, P. R., Johnston, A. E. & Jenkinson, D. S. (1992). Influence of soil type, crop management and weather on recovery of ^{15}N-labelled fertilizer applied to winter wheat in spring. *Journal of Agricultural Science*, *Cambridge* **118**, 83–100.

Ranells, N. N. & Wagger, M. G. (1997). Nitrogen-15 recovery and release by rye and crimson clover crops. *Soil Science Society of America Journal* **61**, 943–948.

Scott, W. R., Martin, R. J. & Stevenson, K. R. (1992). Soil fertility limitations to wheat yield and quality. In *Proceedings of the wheat symposium: limits to production and quality* (Eds W. B. Griffin. K. M. Pollock & H. J. Bezar), pp. 47–56. Canterbury, New Zealand: Lincoln University.

Sisworo, W. H., Mitrosuhardjo, M. M., Rasjid, H. & Myers, R. J. K. (1990). The relative roles of N fixation, fertiliser, crop residues and soil in supplying N in multiple cropping systems in a humid, tropical upland cropping system. *Plant and Soil* **121**, 73–82.

Smiley, R. W., Collins, H. P. & Rasmussen, P. (1996). Disease of wheat in long-term agronomic experiments at Pendleton, Oregon. *Plant Disease* **80**, 813–820.

Staniforth, A. R. (1982). *Straw for Fuel, Feed and Fertiliser?* Ipswich: Farming Press Limited.

Stephen, R. C. (1982). Nitrogen fertilisers in cereal production. In *Nitrogen Fertilisers in New Zealand Agriculture* (Ed. P. D. Lynch), pp. 77–93. Wellington: New Zealand Institute of Agricultural Science.

Swanson, S. P. & Wilhelm, W. W. (1996). Planting date and residue rate effects on growth, partitioning, and yield of corn. *Agronomy Journal* **88**, 205–210.

Ta, T. C. & Faris, M. A. (1990). Availability of N from ^{15}N-labelled alfalfa residues to three succeeding barley crops under field conditions. *Soil Biology and Biochemistry* **22**, 835–838.

Thomsen, I. K. & Jensen, E. S. (1994). Recovery of nitrogen by spring barley following incorporation of ^{15}N-labelled straw and catch crop material. *Agriculture*, *Ecosystems and Environment* **49**, 115–122.

Triplett, G. B. Jr., Haghiri, F. & van Doren, D. M. Jr. (1979). Ploughing effect on corn yield response to N following alfalfa. *Agronomy Journal* **71**, 801–803.

van der Weerden, T. J., Williams, P. H. & Sherlock, R. R. (1998). Nitrous oxide emissions following cultivation of pasture. In *Workshop on the Science of Atmospheric Gases*. 12–13 February (Ed. T. Clarksen). Wellington, New Zealand: National Institute of Water and Atmospheric Research.

Varco, J. J., Frye, W. W., Smith, M. S. & Mackown, C. T. (1989). Tillage effects on nitrogen recovery by corn from a nitrogen-15 labelled legume cover crop. *Soil Science Society of America Journal* **53**, 822–827.

Vigil, M. F., Kissel, D. S. & Smith, S. J. (1991). Field crop recovery and modelling of nitrogen mineralised from labelled sorghum residues. *Soil Science Society of America Journal* **55**, 1031–1037.

Wade, M. K. & Sanchez, P. A. (1983). Mulching and green manure applications for continuous crop production in the Amazon basin. *Agronomy Journal* **75**, 39–45.

Wagger, M. G., Kissel, D. E. & Smith, S. J. (1985). Mineralization of nitrogen from nitrogen-15 labelled crop residues under field conditions. *Soil Science Society of America Journal* **49**, 1220–1226.

Williams, P. H. & Haynes, R. J. (1997). Recovery of N derived from ^{15}N labelled grass/clover residues, recently immobilised urine ^{15}N or native soil organic N by a wheat crop following cultivation of a pasture soil. *Agriculture Ecosystem and Environment* **63**, 67–72.

Winteringham, F. P. W. (1984). *Soil and Fertiliser Nitrogen*. Technical reports Series No. 244. Vienna: International Atomic Energy Agency.

Yaacob, O. & Blair, G. J. (1980). The growth and nitrogen uptake of Rhodes grass grown on soils with varying histories of legume cropping. *Plant and Soil* **57**, 249–255.