Journal of Agricultural Science, *Cambridge* (2001), **137**, 17–25.
DOI: 10.1017/S002185960100106x *Printed in the United Kingdom*

Uptake and residual value of ^{15}N-labelled fertilizer applied to first and second year grass seed crops in New Zealand

[1] *New Zealand Institute for Crop & Food Research Limited, Canterbury Agriculture and Science Centre, Private Bag 4704, Christchurch, New Zealand*
[2] *Seed Technology Institute, PO Box 84, Lincoln University, Canterbury, New Zealand*

(*Revised MS received 22 January 2001*)

SUMMARY

This study was established to quantify the uptake of ^{15}N-labelled nitrogen (urea) applied in the first and second years of perennial ryegrass (*Lolium perenne* L.), tall fescue (*Festuca arundinacea* Schreb.) and browntop (*Agrostis capillaris* L.) seed crops, and the availability of the residual fertilizer N to a subsequent wheat (*Triticum aestivum* L.) crop under field conditions in Canterbury, New Zealand. Total recovery of ^{15}N-labelled nitrogen fertilizer was approximately 100% when fertilizer was applied to the grass seed crops in spring. At harvest in year 1, grass straw and seed contained 34–47% and 6–15% of the applied N respectively; 27–35% remained in the soil (0–150 mm depth). Recovery of ^{15}N in straw and soil was higher in fescue and ryegrass than in browntop, but recovery in roots was lower. At harvest in year 2, most of the ^{15}N was present in the soil (30–37%) with only small amounts in the seed (0·7–1·0%), straw (3·6–4·9%) and roots (5·2–12·7%). In year 3, 2·5–3·5% of the residual ^{15}N was recovered in the wheat and 18–26% in soil. Losses of ^{15}N were minimal until ploughing after the second harvest, when there was an apparent loss of 11–35% of the fertilizer N applied. Losses were not directly associated with the fertilizer but indirectly following release of fertilizer N previously immobilized in plant roots and soil microorganisms. Small losses also occurred directly from autumn-applied N, probably through leaching. Despite these losses, overall there was an accumulation of fertilizer N in the soil organic pool, suggesting that ryegrass fescue and browntop seed crops have a role in contributing to the N fertility of the soil.

INTRODUCTION

Grass seed production is a major land use on the Canterbury Plains located on the eastern side of the South Island of New Zealand. Approximately 34000 ha of herbage seed are grown annually (Rowarth *et al*. 1998). Three of the main grass species grown are perennial ryegrass (*Lolium perenne* L.), tall fescue (*Festuca arundinacea* Schreb.) and browntop (*Agrostis capillaris* L.).

It is generally agreed that in the absence of other limitations, such as soil moisture (Rolston *et al*. 1994), N availability is the major factor influencing seed yields (Rowarth 1997). Many studies have shown the yield benefits that occur when N fertilizer is applied to grass seed crops (Lambert 1956*a*, 1956*b*, Hill 1970, Hebblethwaite & Ivins 1977, Brown & Archie 1986, Hampton 1987, Jin *et al*. 1996, Rowarth *et al*. 1999). In recent years, seed yields have increased steadily due to increased use of N fertilizer and improved timing of N applications (Hampton 1987, Cookson *et al*. 2000*a*). Top ryegrass seed growers are currently using up to 250 kg N/ha and achieve over 2000 kg/ha seed (Rolston & McCloy 1997).

The change in emphasis from maximum production to optimum efficiency, and therefore sustainability within production systems, has resulted in a requirement to know how fertilizer inputs contribute to soil, plant, water and atmosphere pools. Research using lysimeters has shown that the contribution of fertilizer N to ryegrass seed yield is maximized when N is applied to match plant requirement, i.e. a small amount in autumn and late winter with the main addition in early spring (Cookson *et al*. 2000*a*). However, uptake by grass is typically low and

* To whom all correspondence should be addressed. Email: williamsp@crop.cri.nz
† Present address: Graduate School, UNITEC, Private Bag 92025, Auckland, New Zealand.

considerable amounts of fertilizer N remain in the soil after harvest, e.g. 30–70% of the applied N (Rowarth *et al.* 1999) amounting to over 90 kg/ha N (Williams *et al.* 1997, 2000, Cookson *et al.* 2000*b*). The availability of this residual fertilizer N to a subsequent crop, or for leaching, is important in relation to N-use efficiency. Most of the residual N is in organic forms (Cookson *et al.* 2000*b*) and so is likely to be mineralized with time (Williams *et al.* 2000). A glasshouse study following the fate of unused N in a ryegrass seed crop indicated that only a very small proportion (< 7%) of residual N became available to the succeeding crop (Williams *et al.* 2000). In undisturbed soil lysimeters, less than 1% of the applied N (labelled with ^{15}N) was found in the leachate in the winter following harvest and < 2% was taken up by plants by the following spring (Cookson *et al.* 2000*b*). No studies with grass seed crops have been reported where the availability of residual N applied to a subsequent crop has been tested under field conditions.

This study was established to quantify the uptake of ^{15}N-labelled urea applied in the first and second years of perennial ryegrass, tall fescue and browntop seed crops. The availability of the residual fertilizer N to a subsequent wheat (*Triticum aestivum* L.) crop under field conditions was also measured.

MATERIALS AND METHODS

The field trial was carried out on the Crop and Food Research farm near Lincoln in the Canterbury region of New Zealand. The soil type was a Templeton silt loam (Udic Ustochrept, USDA) with a soil organic C content of 2·8%, total N content of 0·22%, pH of 6·2, Olsen P of 35 µg P/g, exchangeable K of 950 µg K/g, exchangeable Ca of 1190 µg Ca/g and exchangeable Mg of 55 µg Mg/g (0–150 mm depth of soil). These soil analyses indicate that P, K, Ca and Mg were not limiting at this site. The site had grown cereal and grain legume crops continuously for > 10 years and was previously in wheat for 2 years.

Year 1 (*March 1995–February 1996*)

The trial was laid out in a randomized block design with the three grass species ('Grasslands Nui' ryegrass, 'Advance' tall fescue and 'Grasslands Sefton' browntop) replicated three times. Each plot was 15 m × 10 m. The grass seed was sown in March 1995 at rates of 5 kg/ha ryegrass, 3 kg/ha fescue and 3 kg/ha browntop. A basal application of 150 kg/ha diammonium phosphate (containing 18% P and 20% N) was applied at sowing. Nitrogen fertilizer (urea containing 46% N) was applied six or seven times during the trial (Table 1). The timing and rate for each application was determined from herbage N concentrations measured regularly throughout the trial (Jin *et al.* 1996, Sicard & Rowarth 1998, Hill *et al.* 1999). The fate of fertilizer N was quantified by treating a subplot (2 m × 2 m) within each mainplot with ^{15}N-labelled urea (5 atom % enrichment) on each fertilization date. A separate subplot was used for each fertilizer application. The ^{15}N-labelled urea was applied to each subplot in four l of water. A further two l of water was applied to wash the urea into the soil and minimize volatilization losses (Black *et al.* 1987). The urea and water solutions were applied to the subplots with a watering can.

The ryegrass and fescue seed crops were harvested by hand on 28 December 1995. The browntop was harvested by hand on 8 February 1996. Harvested material was collected in close weave hessian bags and air dried. The dried samples were threshed with a Kurt Peltz thresher and dressed in a seed cleaner. Following harvest, separate samples for root and soil analysis (0–150 mm) were collected using a 20 mm diameter corer (20 cores per plot). The roots were removed by hand, washed, dried (60 °C) and weighed. Previous measurements have shown that the majority of the grass roots are within the 0–150 mm depth of soil (Williams, unpublished data). Soil, root, straw and seed samples were analysed for total N and ^{15}N.

Year 2 (*March 1996–February 1997*)

Grazing (a typical management practice after harvest) was simulated by mowing the herbage to 30 mm above the soil surface on 7 March 1996. The herbage was removed from the trial area. Herbage from the ^{15}N subplots was weighed, dried and ground for ^{15}N and total N analysis. New N fertilizer and ^{15}N subplots were set up at each fertilization date as outlined in year 1.

In year 2, the fescue was hand harvested on 20 December 1996, the ryegrass on 27 December 1996 and the browntop on 26 February 1997. The samples were processed as described above. Soil and root samples were also collected as in year 1. Soil, root, straw and seed samples were analysed for total N and ^{15}N.

Year 3 (*March 1997–February 1998*)

In April 1997, the trial was sprayed with a herbicide (glyphosate) and ploughed to a depth of 150 mm with a mouldboard plough. The site was secondary cultivated and sown in 'Sapphire' wheat at 184 kg/ha on 9 July 1997. The wheat was sown with 150 kg/ha superphosphate (containing 10% P and 11% S) but no N fertilizer was applied. The wheat was hand harvested on 10 February 1998 and the samples threshed with a Kurt Peltz thresher. Soil and root samples were taken as in previous years 1 and 2. Soil, root, straw and seed samples were analysed for total N and ^{15}N.

Table 1. *Date and amount of N fertilizer (kg N/ha) applied to the grass seed crop*

Date	Ryegrass	Fescue	Browntop
Year 1			
31 July 1995	30	30	30
5 September 1995	60	60	60
3 October 1995	80	80	45
Year 2			
26 March 1996	50	50	50
28 August 1996	50	50	50
23 September 1996	100	100	100
27 November 1996	—	—	50

It is likely that there was some dispersion of ^{15}N during cultivation, seedbed preparation and drilling the wheat crop. This could decrease the recovery of ^{15}N in our soil and plant samples. To minimize this effect, samples were collected from the central 1 m × 1 m area of the plots. The original plots were 2 m × 2 m so this left a wide zone around the edges of the plots that was not sampled. The detailed study of Follett *et al.* (1991) showed that dispersion effects in the central 1 m × 1 m area would be minimal. Samples were collected to a 150 mm depth as this was the depth of cultivation.

Trial management

The grass seed and wheat crops were managed in accordance with local farm management practices. Weeds, pests and diseases were controlled with prophylactic chemicals. Total rainfall during the trial was 531 mm in year 1, 630 mm in year 2 and 870 mm in year 3 (the long term mean rainfall is 680 mm). Each year the trial was irrigated with 100–150 mm of water between November and February as required to ensure soil moisture was not limiting.

Soil, root, straw and seed samples were analysed for total N and ^{15}N on a Tracer-mass stable isotope analyser in conjunction with a Roboprep-CN biological sample converter. Recovery of the ^{15}N in the soil and herbage was calculated using the formula recommended by Hauck & Bremner (1976). Ammonium and nitrate were extracted from the soil samples with 2 M KCl and measured using the colorimetric methods described by Keeney & Nelson (1982).

Data were analysed by analysis of variance using the Genstat statistical package (Genstat 1998).

RESULTS

Yields

All subplots received the same rate of N fertilizer, hence yields were similar in all the ^{15}N treatments; results presented (Table 2) are the means for all the subplots for each grass species. In the first year, mean yields of grass seed were high, equalling top reported yields (Rowarth 1997) (Table 2). In the second year, yield of ryegrass was half that of the first year. This yield decline is common (Hampton & Rowarth 1998, Young *et al.* 1998) and may be due to inter-plant competition (Young & Youngberg 1996).

The straw yields of the grasses were similar in both years, with 9720–12 360 kg DM/ha produced in the first year and 8990–13 130 kg DM/ha in the second year. Browntop produced more straw than ryegrass or fescue in both years. Root production increased from 2480–2910 kg DM/ha in the first year to 4440–11 340 kg DM/ha in the second year as the perennial grass plants became more established. This increase in root mass was particularly noticeable for fescue and browntop.

Wheat yield was low (2720–3750 kg/ha) compared with the regional average of 5500 kg/ha (Statistics New Zealand 1997). However, the wheat in this experiment was grown without N fertilizer, to encourage the plants to scavenge for the residual fertilizer N applied to the grass seed crops. Typically wheat crops receive 150–200 kg N/ha during crop growth to reach target yields of 6000 kg/ha (Morton *et al.* 1998).

Recovery of ^{15}N from fertilizer applied in spring year 1

In the first year, ^{15}N-fertilizer was applied in late winter/spring (July, September and October; Table 1). As there was no difference in the fate of the ^{15}N between these three dates results have been combined. Total recovery of ^{15}N in the seed, straw, roots and soil, at the time of seed harvest in year 1, ranged from 91% for browntop to 104% for ryegrass (Table 3). These differences were not statistically significant indicating that the losses of N through gaseous emission and leaching were minimal. Recovery of ^{15}N in the straw and soil was lower in the browntop compared with the fescue and ryegrass but this was partly compensated for by a greater recovery in

Table 2. *Yields of seed, straw and roots for the grass seed and wheat crops. Degrees of freedom for year 1 = 21, year 2 = 17 and wheat = 37*

Yield	Ryegrass	Fescue	Browntop	S.E.
Seed yield (kg/ha)				
Grass year 1 (1996)	2000	770	910	57
Grass year 2 (1997)	900	670	1090	105
Wheat (1998)	2700	1820	2420	346
Straw yield (kg DM/ha)				
Grass year 1 (1996)	10330	9720	12360	484
Grass year 2 (1997)	8990	10160	13130	1013
Wheat (1998)	3750	2720	3150	284
Root yield (kg DM/ha)				
Grass year 1 (1996)	2910	2540	2480	226
Grass year 2 (1997)	4440	8750	11340	2077
Wheat (1998)	380	460	380	74

Table 3. *Recovery of ^{15}N in soil, grass seed crops, mown herbage and wheat over a 3 year period following application of ^{15}N-fertilizer in late winter/spring in year 1. Values are expressed as a percentage of the ^{15}N applied. Degrees of freedom = 21*

	Ryegrass	Fescue	Browntop	S.E
Year 1				
Seed	15·0	6·0	8·0	0·6
Straw	47·0	46·0	34·0	3·3
Roots	13·0	16·0	22·0	1·7
Soil (0–150 mm)	29·0	35·0	27·0	1·7
Total	104·0	103·0	91·0	5·2
Year 2				
Grazed herbage	2·7	2·7	1·2	0·79
Seed	0·7	1·0	1·0	0·22
Straw	4·9	4·3	3·6	1·29
Roots	5·2	12·7	9·9	1·51
Soil (0–150 mm)	30	37·0	32·0	1·67
Total	43	58·0	48·0	2·52
Year 3 (wheat)				
Seed	1·4	1·2	1·5	0·38
Straw	0·7	0·6	0·7	0·13
Roots	0·2	0·2	0·3	0·15
Soil (0–150 mm)	21·0	24·0	21·0	3·56
Total	24·0	27·0	24·0	2·41
Total recovery year 1–year 3*	94·0	86·0	71·0	10·7

* Total recovery in year 1 seed and straw, year 2 mown herbage, seed and straw and year 3 seed, straw, roots and soil.

browntop roots. Less ^{15}N was recovered in the fescue seed compared with the ryegrass seed but more was recovered in the soil.

At harvest time, most of the ^{15}N was recovered from the plants (34–47% and 6–15% in the straw and seed respectively); only 27–35% of the applied ^{15}N remained in the soil. Mineral N concentrations were low at harvest (<4 μg N/g; data not presented) indicating that most of the ^{15}N was in the soil organic pool. Between 13–22% of the applied ^{15}N was in the plant roots.

Of the ^{15}N applied, 42–51% remained in the roots and soil at the time of the first seed harvest (December 1995/February 1996). Most of this could be accounted for at the harvest of the second seed crop in December 1996/February 1997 (Table 3). At this second harvest, most of the ^{15}N was present in the soil (30–37% of the ^{15}N applied) with only small amounts in the seed (0·7–1·0%), straw (3·6–4·9%) and roots (5·2–12·7%). Removal of the above ground herbage in March 1996 to simulate grazing removed a further 1·2–2·7% of the ^{15}N.

In year 3, the grass plots were ploughed and a wheat crop was sown. When the wheat was harvested (January 1998), 21–24% of the ^{15}N applied in year 1 was still present in the soil (Table 3). A further 1·2–1·5% was in the wheat grain, 0·6–0·7% was in the straw and 0·2–0·3% was in the roots. The amount recovered in the soil and wheat plants (24–27%) was lower than that remaining in the soil and roots at the end of year 2 (35–50%) indicating that some of the ^{15}N was lost during year 3 when the wheat crop was grown.

Over the whole three year period, 50–72% of the fertilizer was taken up by the above ground biomass but only 8–17% was removed in the harvested seed. Between 71 and 94% of the ^{15}N applied was accounted for.

Recovery of ^{15}N from fertilizer applied in autumn year 2

Fertilizer N (50 kg N/ha) was applied in March 1996 following the grass seed harvest in year 1. By

Table 4. *Recovery of ^{15}N in soil, grass seed crops and wheat over a 2 year period following application of ^{15}N-fertilizer in autumn in year 2. Values are expressed as a percentage of the ^{15}N applied. Degrees of freedom = 4*

	Ryegrass	Fescue	Browntop	S.E.
Year 2				
Grass seed	1·0	1·4	2·4	0·30
Straw	17·0	8·0	11·0	0·56
Roots	12·0	13·0	18·0	2·89
Soil (0–150 mm)	51·0	34·0	38·0	6·43
Total	86·0	59·0	71·0	1·85
Year 3 (wheat)				
Seed	2·0	1·2	2·1	0·23
Straw	1·0	0·6	1·1	0·14
Roots	0·1	0·3	0·2	0·03
Soil (0–150 mm)	36·0	26·0	24·0	5·81
Total	39·0	28·0	27·0	5·59
Total recovery year 2–year 3*	57·0	38·0	40·0	4·53

* Total recovery in year 2 mown herbage, seed and straw and year 3 seed, straw, roots and soil.

Table 5. *Recovery of ^{15}N in soil, grass seed crops and wheat over a 2 year period following application of ^{15}N-fertilizer in spring in year 2. Values are expressed as a percentage of the ^{15}N applied. Degrees of freedom = 8*

	Ryegrass	Fescue	Browntop	S.E.
Year 2				
Seed	4·0	4·0	6·0	0·62
Straw	45·0	33·0	26·0	7·64
Roots	19·0	29·0	19·0	5·66
Soil (0–150 mm)	37·0	33·0	31·0	3·96
Total	105·0	99·0	81·0	9·54
Year 3 (wheat)				
Seed	2·0	1·5	2·3	0·52
Straw	1·0	0·7	1·0	0·29
Roots	0·2	0·3	0·2	0·11
Soil (0–150 mm)	18·0	26·0	20·0	3·68
Total	21·0	28·0	24·0	3·61
Total recovery year 2–year 3*	70·0	65·0	56·0	8·91

* Total recovery in year 2 grazed herbage, seed and straw and year 3 seed, straw, roots and soil.

December 1996/February 1997, only 59–86% of this ^{15}N was accounted for in the soil and herbage (Table 4), indicating that some of the autumn-applied N had been lost from the soil–plant system. Leaching was the most probable loss mechanism as there was above average rainfall in April, June and July 1996.

At harvest of the grass seed crops, 47–63% of the ^{15}N applied in the autumn remained in the soil and roots. When the wheat was harvested, 27–39% of the applied ^{15}N was recovered in the soil and wheat plants. Thus, there appeared to be a loss of N during the growing of this crop.

Recovery of ^{15}N from fertilizer applied in year 2 spring

In year 2, fertilizer N was applied in spring during August and September 1996. An extra application was made to the browntop plots in November 1996. As in year 1, there were no differences in the fate of the ^{15}N between these three dates so results have been combined. At harvest in December 1996/February 1997, 31–37% of the ^{15}N was in the soil (Table 5). Mineral N was low (< 4 μg N/g; data not presented), suggesting ^{15}N was present as organic N. Seed contained 4–6% of the ^{15}N while 26–45% was in the straw. Although the total recovery of ^{15}N in the browntop treatment was 81% compared with 99–105% for the other grasses, the difference was not statistically significant, indicating that all the ^{15}N applied could be accounted for and losses were minimal.

The plots receiving fertilizer in year 2 were ploughed and sown to wheat as outlined previously. When the wheat was harvested, 18–26% of the applied ^{15}N was recovered in the soil (Table 5). Plant uptake accounted for 2·5–3·5%, so approximately 21–28% of the fertilizer N was recovered in year 3. This came from the 50–62% of the fertilizer ^{15}N which remained in the soil and plant roots after harvest in year 2. The overall balance for the ^{15}N applied to the grass crops in the spring year 2, shows that only 56–70% could be accounted for in harvested herbage and remaining in the soil (Table 5). Since most of the applied ^{15}N could be accounted for after the grass seed harvest, the unaccounted for ^{15}N was presumably lost during the wheat crop.

N balance

The amount of N applied to the grass seed crops, removed in the seed and straw and mown herbage are shown in Table 6. Overall 370–385 kg N/ha were applied in fertilizer. The amounts of N removed in the harvested seed over the 2 years were 34 kg N/ha in the fescue seed, 51 kg N/ha in the browntop and 59 kg N/ha in the ryegrass seed. Grass seed straw accounted for another 190–245 kg/ha. A further 32–47 kg N/ha were removed in the wheat grain and 14–18 kg N/ha in the wheat straw.

Soil N content

The total soil N content measured at the start of the trial (0·23% N) was similar to that at the end of the

Table 6. *Amount of N applied in fertilizer and measured in seed, straw and roots for grass seed and wheat (kg N/ha). Degrees of freedom for year 1 = 21, year 2 = 17 and wheat = 37*

	Ryegrass	Fescue	Browntop	S.E.
Year 1				
N applied	170	170	135	
Seed	44	19	25	1·7
Straw	130	159	91	10·9
Roots	63	60	67	5·0
N in grazed herbage	25	17	10	4·0
Year 2				
N applied	200	200	250	
Seed	15	15	26	0·9
Straw	110	86	99	7·1
Roots	68	104	121	11·2
Year 3 (wheat)				
N applied	0	0	0	
Seed	47	32	45	2·8
Straw	15	14	18	1·1
Roots	4	6	4	0·8

trial (0·22% N). Mineral N measured at crop harvest in 1996, 1997 and 1998 was always low (< 4 μg N/g; data not presented).

DISCUSSION

The uptake of ^{15}N-labelled fertilizer applied in spring by the three grass species appears to be similar. Previous research has shown that all three species respond to N applied in the spring, although there may be inter-species differences in the optimum time to apply the fertilizer (Jin *et al.* 1996, Rowarth 1997). In our study, herbage N analyses were used to determine the time and rate of N fertilizer to apply during the spring. Detailed measurements of soil ^{15}N and plant uptake were not made immediately after fertilizer was applied, so no conclusions can be drawn about differences in N uptake and N partitioning between species in the short term. However, by harvest time there was a similar proportion of ^{15}N taken up by the plants, tops and roots regardless of species or the time the fertilizer was applied in spring.

The grass roots were a major sink for fertilizer N. Of the ^{15}N applied in spring, 13–29% was recovered in the grass roots at harvest. This is quite different to cereal crops like wheat, the roots of which contain only a small proportion of the fertilizer N at harvest, e.g. 3% (Recous *et al.* 1988). However, it is probable that more of the fertilizer N applied to wheat plants will be in the above ground biomass. Studies show that up to 80% of fertilizer N applied to wheat can be recovered in above ground biomass (MacDonald *et al.* 1989) compared with 32–62% for grasses in this study. The difference is due to the extensive root system produced by grass plants compared with wheat plants. The grass root weight in our study was about 3000 kg DM/ha in year 1 and a total of 11000 kg DM/ha by the end of year 2, whereas wheat plants had 300 kg root DM/ha at harvest. Even higher yielding wheat crops yielding 10 t grain/ha produce only 800 kg root DM/ha (Recous *et al.* 1988). Grasses are grown in crop rotations as break crops to provide organic matter to the soil and assist in stabilizing soil structure (Francis *et al.* 1999). The grass roots are particularly important for adding organic matter to the soil, encouraging microbial biomass and physically binding soil aggregates together (Haynes & Beare 1996). Our results show that grass crops managed for seed production may also make an important contribution to the maintenance of soil organic N in cultivated soils.

Uptake of ^{15}N-fertilizer by the grass plants from the autumn application was similar between the grass species but was not as high as from the spring applications. Plants recovered 25–35% of the ^{15}N applied in autumn in the roots and above ground herbage compared with 50–68% from the spring applications. In the spring, plant growth is rapid and N uptake is high but N availability is often limited by mineralization and so responses to N fertilizer often occur. During autumn, plant growth and uptake of N is slower than in spring due to decreased temperatures and lower light intensity (Ledgard *et al.* 1988). Cookson *et al.* (2001) also reported lower recoveries in ryegrass from autumn applied ^{15}N in Canterbury but they found this was compensated for by the retention of higher amounts of fertilizer N in the roots and soil. This trend was not apparent in our study, however we were not able to account for 14–41% of the autumn applied ^{15}N in the plants or soil at harvest time, probably due to losses of N through leaching or gaseous emission over winter. The four month period following application had higher than average rainfall so leaching was likely. We estimated that 110 mm of drainage may have occurred during this period (G. Francis pers. comm.). Losses through denitrification may also have occurred; Cookson *et al.* (2001) reported that 24% of the fertilizer N may be lost by denitrification under similar winter conditions in Canterbury.

Although losses of N from autumn applied N occurred in our study, such losses do not always occur from autumn application. In a previous study no losses were apparent following application of 30 kg N/ha in late April to a ryegrass seed crop in Canterbury (Williams *et al.* 2000). Nitrate leaching depends on a combination of drainage and soil nitrate content, both of which are variable between seasons and sites. From a lysimeter study in Canterbury, Cookson *et al.* (2000*c*) reported that 6–8% of fertilizer N applied in the autumn leached over winter and suggested that application of fertilizer N in

Table 7. *Apparent losses of ^{15}N and N fertilizer following cultivation of grass seed crops. This was calculated as the difference between ^{15}N remaining in the soil and roots when the grass was ploughed down in year 2 and the recovery of ^{15}N in the soil and wheat in year 3*

	Ryegrass	Fescue	Browntop
Fertilizer applied in late winter/spring year 1			
^{15}N lost (%)*	11	23	17
Fertilizer lost (kg N/ha)	19	39	23
Fertilizer applied in autumn year 2			
^{15}N lost (%)*	24	19	29
Fertilizer lost (kg N/ha)	12	8	15
Fertilizer applied in spring year 2			
^{15}N lost (%)*	35	34	26
Fertilizer lost (kg N/ha)	70	51	52

* Expressed as a percentage of the ^{15}N applied.

March/April (autumn) has a higher risk of being lost compared with applications in the spring. A number of studies in Canterbury have now shown that the risk of losses from spring applications is low (Cookson *et al*. 2001, Williams *et al*. 2000) due to a combination of low drainage rate and low soil mineral N content brought about by rapid plant uptake of N (Francis 1995). Although application of fertilizer N may increase soil mineral N, this effect is short lived due to rapid uptake by the plants and immobilization of N by the soil microorganisms (Williams & Haynes 2000).

Recovery of ^{15}N from spring applications in year 1 and year 2 were similar but recoveries were less in year 3. Using the data in Table 3, we calculated the apparent loss of ^{15}N during year 3 (Table 7) as the difference between the ^{15}N remaining in the roots and soil at the end of year 2 (prior to ploughing) and the ^{15}N recovered in the soil and wheat crop at the end of year 3. All the values are expressed as a percentage of the ^{15}N applied in the spring in year 1. Similar calculations were carried out for the ^{15}N applied in the autumn and spring of year 2. The calculations in Table 7 show that of the fertilizer applied in year 1, 11–23% could not be accounted for in year 3. This was equivalent to 19–39 kg N/ha of the applied fertilizer. In year 2 the losses were higher with 26–35% of the spring fertilizer N not accounted for, which was equivalent to 51–52 kg N/ha. The amount of ^{15}N lost appears to be proportional to the amount of ^{15}N remaining in the soil and roots at the end of year 2. These losses are thought to be associated with cultivation of the soil between the grass and wheat crops. In April 1997, the grasses were ploughed down and the area was planted in winter wheat. Significant mineralization of the plant residue N may have occurred after cultivation (Francis 1995). The wheat plants, which were sown in July, would have been too small to recover much of the mineralized N which may be lost via leaching or emission of gases. Cultivation of pasture in autumn and sowing to winter wheat has been shown to enhance leaching losses (Francis 1995). In addition, the winter period of year 3 had above average rainfall which could have increased the potential for leaching.

Another explanation for the reduced recovery of ^{15}N is that some of the ^{15}N could have been dispersed vertically or horizontally during cultivation and so was outside the sampling area. As explained previously, to minimize this effect samples were collected from the central 1 m × 1 m area of the original 2 m × 2 m subplots. The depth of cultivation was 150 mm and soil samples were collected to 150 mm depth. Care was taken during ploughing to ensure the depth of cultivation did not exceed this depth. Given the high rates of mineralization that have been measured following cultivation of grass residues (Francis 1995), it is most likely that mineralization followed by leaching is the reason for the apparent loss of ^{15}N following ploughing rather than displacement of labelled soil and residues.

Incorporation of ^{15}N into soil organic matter accounted for 27–37% of the ^{15}N applied in spring and 34–51% of the ^{15}N applied in autumn. This incorporation could have occurred through microbial activity or inputs in plant debris. Immobilization of applied N by the microbial biomass can be extremely rapid in the rhizosphere of grass roots (Williams & Haynes 2000) and provides an alternative pathway to plant uptake in soil–plant systems. Although applying fertilizer N frequently at low rates undoubtedly increases the N recovery efficiency by plants, when microbial activity is high there is competition for the fertilizer N. We found that only 1·9–3·5% of the fertilizer N applied was recovered in the subsequent wheat crop (grain, straw and roots). This agrees well with the 1·1–2·5% reported by Hart *et al*. (1993) from a field experiment measuring the recovery of fertilizer

N applied to wheat by a subsequent wheat crop. Since the recovery of residual fertilizer N by wheat plants appears to be relatively low, we assume that most of the plant N (estimated to be 87–95%) originated from the rest of the soil organic N pool. However, the proportion of the fertilizer N recovered may be quite high compared with the proportion of the organic N pool taken up. This was the case in a glasshouse study where wheat recovered 7–13% of the residual fertilizer N but only 1·5–3·1% of the soil organic N (Williams *et al.* 2000).

Fertilizer N applied to all three grass seed crops accumulated in the soil as organic N. The total amount of fertilizer applied to each crop was in excess of the amount of N removed in the seed and, even allowing for some losses following cultivation and sowing of the next crop, there was still a net gain in soil N. Table 6 shows that for a 2 year ryegrass seed crop receiving 370 kg/ha of N fertilizer, 60 kg N/ha may be removed in the harvested grass seed. If the ryegrass straw is baled and removed each year a further 120 kg N/ha may be removed (assuming half the straw is baled). This results in a net gain of 190 kg N/ha over 2 years. Similar rates of N accumulation (90 kg N/ha per year) were measured in previous studies on ryegrass seed crops (Williams *et al.* 2000). Although only a small proportion of this will become available to the next crop and there is a risk of losing part of the accumulated N following cultivation, there is a contribution to the long-term N supply of the soil. This contribution is similar to that from clover seed crops and grazed pastures and considerably more than the contribution from cereal crops (< 30 kg N/ha; Haynes 1994).

CONCLUSIONS

The fertilizer N applied to ryegrass, fescue and browntop seed crops in the spring was either taken up by the plants or incorporated into soil organic matter. Ploughing the grasses in the autumn and sowing winter wheat resulted in the apparent loss of 11–35% of the fertilizer N applied. Losses were associated not with the fertilizer directly but indirectly following release of N previously immobilized in plant roots and soil microorganisms. Small losses also occurred directly from N fertilizer applied in the autumn presumably through leaching after application. Despite these losses, overall there was an accumulation of fertilizer N in the soil organic pool. This shows that ryegrass, fescue and browntop seed crops have a role in contributing to the N fertility of the soil and hence are important crops to include in a crop rotation.

We thank Richard Gillespie for managing the field trial. This research programme was funded by the Foundation for Research, Science & Technology (CO2613).

REFERENCES

Black, A. S., Sherlock, R. R. & Smith, N. P. (1987). Effect of timing of simulated rainfall on ammonia volatilization from urea applied to soil at varying moisture content. *Journal of Soil Science* **38**, 679–687.

Brown, K. R. & Archie, W. J. (1986). Effect of nitrogen application on seed production of 'Grasslands Egmont' and 'Grasslands Sefton' browntops (*Agrostis capillaris*). *New Zealand Journal of Experimental Agriculture* **14**, 257–260.

Cookson, W. R., Rowarth, J. S., Cornforth, I. S. & Cameron, K. C. (1999). Sustainability issues with nitrogen fertiliser use in perennial ryegrass (*Lolium perenne* L.) seed crops. *Journal of Applied Seed Production* **17**, 67–76.

Cookson, W. R., Rowarth, J. S. & Cameron, K. C. (2000*a*). The response of a perennial ryegrass (*Lolium perenne* L.) seed crop to nitrogen fertiliser in the absence of moisture stress. *Grass and Forage Science* **55**, 314–325.

Cookson, W. R., Rowarth, J. S. & Cameron, K. C. (2000*b*). The fate of residual nitrogen after a perennial ryegrass (*Lolium perenne* L.) seed crop. *Australian Journal of Agricultural Research* **51**, 287–294.

Cookson, W. R., Rowarth, J. S. & Cameron, K. C. (2001). The fate of autumn-, late winter- and spring-applied nitrogen fertilizer in a perennial ryegrass (*Lolium perenne* L.) seed crop on a silt loam soil in Canterbury, New Zealand. *Agriculture, Ecosystems and Environment* **84**, 67–77.

Cookson, W. R., Rowarth, J. S. & Cameron, K. C. (2000*c*). The effect of autumn-applied ^{15}nitrogen fertilizer on winter leaching in a cultivated soil. *Nutrient Cycling in Agroecosystems* **56**, 99–107.

Follett, R. F., Porter, L. K. & Halvorson, A. D. (1991). Border effects on Nitrogen-15 fertilized winter wheat microplots grown in the Great Plains. *Agronomy Journal* **83**, 608–612.

Francis, G. S. (1995). Minimising nitrate leaching losses following cultivation of temporary leguminous pastures in mixed cropping rotations in Canterbury, New Zealand. *Journal of Contaminants Hydrology* **20**, 313–327.

Francis, G. S., Tabley, F. J. & White, K. M. (1999). Restorative crops for the amelioration of degraded soil conditions in New Zealand. *Australian Journal of Soil Research* **37**, 1017–1034.

Genstat (1998). *Genstat 5 Release 4.1*. Reference Manual Supplement. NAG, Oxford.

Hampton, J. G. (1987). Effect of nitrogen rate and time of application on seed yield in perennial ryegrass cv. Grasslands Nui. *New Zealand Journal of Experimental Agriculture* **15**, 9–16.

Hampton, J. G. & Rowarth, J. S. (1998). Ryegrass. In *Herbage Seedcrop Management* (Ed. J. S. Rowarth), pp. 67–76. Lincoln, New Zealand: Lincoln University Press.

Hart, P. B. S., Powlson, D. S., Poulton, P. R., Johnston, A. E. & Jenkinson, D. S. (1993). The availability of nitrogen in the crop residues of winter wheat to subsequent crops. *Journal of Agricultural Science, Cambridge* **121**, 355–362.

Hauck, R. D. & Bremner, J. M. (1976). Uses of tracers for soil and fertilizer research. *Advances in Agronomy* **28**, 219–265.

HAYNES, R. J. (1994) Impact of management practices on nutrient cycling. In *Soil Biota. Management in Sustainable Farming Systems* (Eds C. E. Pankhurst, B. M. Doube, V. V. S. R. Gupta & P. R. Grace), pp. 172–181. CSIRO.

HAYNES, R. J. & BEARE, M. H. (1996). Aggregation and organic carbon storage in Mesothermal humid soils. In *Structure and Organic Matter Storage in Agricultural Soils* (Eds M. R. Carter & B. A. Stewart), pp. 213–262. Boca Raton, Fl: CRC Press.

HEBBLETHWAITE, P. D. & IVINS, J. D. (1997). Nitrogen studies in *Lolium perenne* grown for seed. I. Level of application. *Journal of British Grassland Society* **32**, 195–204.

HILL, M. J. (1970). Ryegrass seed crop management. *New Zealand Journal of Agriculture* **121**, 52–54.

HILL, M. J., HAMPTON, J. G. & ROWARTH, J. S. (1999). Herbage seeds. In *New Zealand Pasture and Crop Science* (Eds J. White & J. Hodgson), pp. 249–262. Auckland: Oxford University Press.

JIN, Q. F., ROWARTH, J. S., SCOTT, W. R. & SEDCOLE, J. R. (1996). A study of nitrogen use in a browntop (*Agrostis capillaris* L.) seed crop. *Journal of Applied Seed Production* **B14**, 31–39.

KEENEY, D. R. & NELSON, D. W. (1982). Nitrogen-inorganic forms. In *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties* (Eds A. L. Page, R. H. Miller & D. R. Keeney), pp. 643–709. Madison, Wisconsin: American Society of Agronomy.

LAMBERT, J. P. (1956*a*). Seed production studies. I. The effect of nitrogenous fertiliser, applied at different rates and dates, on seed production in cocksfoot (*Dactylis glomerata* L.). *New Zealand Journal of Science and Technology* **37A**, 432–442.

LAMBERT, J. P. (1956*b*). Seed production studies. II. The effect of nitrogenous fertiliser, applied at different rates and dates, on seed production in timothy (*Phleum pratense* L.). *New Zealand Journal of Science and Technology* **37A**, 432–442.

LEDGARD, S. F., STEELE, K. W. & FEYTER, C. (1988). Influence of time of application on the fate of ^{15}N-labelled urea applied to dairy pasture. *New Journal of Agricultural Research* **31**, 87–91.

MACDONALD, A. J., POWLSON, D. S., POULTON, P. R. & JENKINSON, D. S. (1989). Unused fertiliser nitrogen in arable soils – its contribution to nitrate leaching. *Journal of the Science of Food and Agriculture* **46**, 407–419.

MORTON, J., CRAIGHEAD, M. & STEVENSON, K. (1998). *Managing soil fertility on cropping farms*. New Zealand Fertiliser Manufacturers' Research Association and New Zealand Pastoral Agriculture Research Institute.

RECOUS, S., MACHET, J. M. & MARY, B. (1988). The fate of labelled ^{15}N urea and ammonium nitrate applied to a winter wheat crop. II. Plant uptake and N efficiency. *Plant and Soil* **112**, 215–224.

ROLSTON, M. P. & MCCLOY, B. L. (1997). Ryegrass 2000: technology transfer in ryegrass seed production. *Proceedings of the Agronomy Society of New Zealand* **27**, 5–8.

ROLSTON, M. P., ROWARTH, J. S., DEFILIPPI, J. M. & ARCHIE, W. J. (1994). Effects of water and nitrogen on lodging, head numbers and seed yield of perennial ryegrass. *Proceedings of the Agronomy Society of New Zealand* **24**, 91–94.

ROWARTH, J. S. (1997). Nutrient and moisture inputs for grass seed yield: an invited review. *Journal of Applied Seed Production* **15**, 103–110.

ROWARTH, J. S. (1998). Browntop. In *Herbage Seedcrop Management* (Ed. J. S. Rowarth), pp. 37–41. Lincoln, New Zealand: Lincoln University Press.

ROWARTH, J. S., CLIFFORD, P. T. P., ARCHIE, W. J. & GUY, B. R. (1993). Technology transfer and the seed industry; a success story. *Proceedings of the Agronomy Society of New Zealand* **28**, 113–115.

ROWARTH, J. S., HAMPTON, J. G. & HILL, M. J. (1998). Survival of the New Zealand herbage seed industry: quality is the answer. *Proceedings of the Agronomy Society of New Zealand* **28**, 21–30.

ROWARTH, J. S., COOKSON, W. R., WILLIAMS, P. H. & CAMERON, K. C. (1999). Fate of nitrogen in ryegrass seed crops – can we alter destiny. *Proceedings of the 4th International Herbage Seed Production Conference* , 91–95.

SICARD, G. & ROWARTH, J. S. (1998). The relationship between applied nitrogen, concentration of nitrogen in herbage and seed yield in perennial ryegrass (*Lolium perenne* L.). III. cv. Palmer at two sites in France. *Journal of Applied Seed Production* **16**, 125–132.

STATISTICS NEW ZEALAND (1997). Agriculture Statistics 1994–95. Statistics New Zealand, Wellington, New Zealand.

WILLIAMS, P. H., ROWARTH, J. S. & TREGURTHA, R. J. (1997). Influence of a perennial ryegrass seed crop on soil nitrogen status. *Proceedings of the Agronomy Society of New Zealand* **27**, 15–18.

WILLIAMS, P. H., ROWARTH, J. S. & TREGURTHA, R. J. (2000). Recovery of ^{15}N-labelled fertilizer by a perennial seed crop and a subsequent wheat crop. *Nutrient Cycling in Agroecosystems* **56**, 117–123.

WILLIAMS, P. H. & HAYNES, R. J. (2000). Transformations and plant uptake of urine N and S in long and short-term pastures. *Nutrient Cycling in Agroecosystems* **56**, 109–116.

YOUNG, W. C. III & YOUNGBERG, H. W. (1996). Cropping systems for perennial ryegrass seed production. II. Minimum tillage systems for changing cultivars in certified seed production. *Agronomy Journal* **88**, 78–82.

YOUNG, W. C. III, SILBERSTEIN, T. B, CHASTAIN, T. G. & ROWARTH, J. S. (1998). The relationship between applied nitrogen, concentration of nitrogen in herbage and seed yield in perennial ryegrass (*Lolium perenne* L.) II. Cultivars in Oregon. *Journal of Applied Seed Production* **16**, 115–124.