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The nitrogen cycle in the Broadbalk Wheat Experiment: recovery and losses of ^{15}N-labelled fertilizer applied in spring and inputs of nitrogen from the atmosphere

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SUMMARY

^{15}N-labelled nitrogen fertilizer (containing equal quantities of ammonium-N and nitrate-N) was applied in 4 consecutive years (1980–3) to different microplots located within the Broadbalk Wheat Experiment at Rothamsted, an experiment which has carried winter wheat continuously since 1843. Plots receiving 48, 96, 144 and 192 kg N/ha every year were given labelled fertilizer in mid-April at (nominally) these rates.

Grain yields ranged from 1–2 t/ha on plots given no N fertilizer since 1843 to a maximum of 7·3 t/ha with 196 kg N/ha. On plots given adequate P and K fertilizer, between 51 and 68% of the labelled N was recovered in the above-ground crop; only about 40% was recovered where P deficiency limited crop growth. In 1981 fertilizer-derived N retained in soil (0–70 cm) at harvest increased from 16 kg/ha, where 48 kg/ha was applied, to 38 kg/ha, where 192 kg/ha was applied. More than 80% of this retained N was in the plough layer (0–23 cm).

Overall recovery of fertilizer N in crop plus soil ranged from 70% to more than 90% over the 4 years of the experiments. Losses of N were larger in years when spring rainfall was above average and when soil moisture deficits shortly after application were small.

Crop uptake of unlabelled N derived from soil increased from 28 kg N/ha on the plot given no fertilizer N to 67 kg N/ha on the plot given 144 kg N/ha. The extra uptake of unlabelled N was mainly, if not entirely, due to greater mineralization of soil N in the plots that had been given N fertilizer for many years. Presumably fertilizer N increased the annual return of crop residues, which in turn led to an accumulation of mineralizable organic N, although there was only a small increase in total soil N content.

Wheat given NH_4-N grew less well and took up less N than wheat given NO_3-N in the relatively dry spring of 1980; there was little difference between the two forms of N in the wetter spring of 1981. In both years more fertilizer N was retained in the soil at harvest when fertilizer was applied as NH_4-N than as NO_3-N.

The N content of the soil in several plots of the experiment has been constant for many years, so that the annual removal of N is balanced by the annual input. A nitrogen balance for the plot given 144 kg fertilizer N/ha showed an average annual input of non-fertilizer N of at least 48 kg/ha, of which N in rain and seed accounts for about 14 kg/ha. The remainder may come from biological fixation of atmospheric N_2 by blue-green algae, or from dry deposition of oxides of nitrogen and/or NH_3 onto crop and soil. The overall annual loss of N from the crop–soil system on this particular plot was 54 kg N/ha per year, 28% of the total annual input from fertilizer and non-fertilizer N.

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Table 1. *Details of field operations*

Operation	Year 1979–80	1980–1	1981–2	1982–3
Chalk applied (2·9 t/ha)	—	—	11 Sept.	—
P, K and Mg applied* (not to plot 10)	24–25 Sept.	8 Sept.	21 Sept.	16 Sept.
Ploughed to 23 cm	27 Sept.	11 Sept.	28 Sept.	20 Sept.
Seedbed prepared	1 and 2 Oct.	30 Sept.	14 Oct.	28 Oct. and 4 Nov.
Winter wheat var. Flanders, drilled at 200 kg/ha	4 Oct.	1 Oct.	16 Oct.	4 Nov.
N applied (^{15}N microplots)	16–17 Apr.	14 Apr.	16 Apr.	15 Apr.
N applied (unlabelled areas)	10 Apr.	15 Apr.	15 Apr.	15 Apr.
Hand harvested (^{15}N microplots)	18 Aug.	13 Aug.	3–4 Aug.	8 Aug.
Combine harvested (unlabelled areas)	21 Aug.	19 Aug.	20 Aug.	10 Aug.
Soils sampled	1–5 Sept.	24–28 Aug.	23–27 Aug.	23 Aug.

* 35 kg P/ha as single superphosphate and 90 kg K/ha as K_2SO_4 applied annually. 35 kg Mg/ha as kieserite applied every 3rd year.

INTRODUCTION

The Broadbalk Continuous Winter Wheat Experiment at Rothamsted (Johnston & Garner, 1969; Dyke *et al.* 1983) provides a unique test-bed for investigating N balances in the crop–soil system, many of the plots having received the same fertilizer treatment every year since 1852. Soil N contents have been virtually constant since 1881 in plots given the same application of inorganic fertilizer for many years (Jenkinson, 1977), so that steady-state conditions can be assumed to hold, with the annual production of soil organic N equal to the amount mineralized each year. In such plots, it is possible to calculate the overall losses and gains of N by the crop–soil system by applying a single pulse of ^{15}N-labelled fertilizer to a plot, at the same rate of N as the customary dressing of unlabelled N. This was done by establishing microplots within certain of the old plots on a section of Broadbalk that carries winter wheat every year. The crop within the microplots was given ^{15}N-labelled nitrogen fertilizer at the same time, and at the same rate of N, as the surrounding plot received its (unlabelled) fertilizer N.

The aims of the work described in this paper were first, to see how the recovery of spring-applied fertilizer N in the crop–soil system varies with the quantity and chemical form of the N applied, and with season, secondly, to measure the quantity of N supplied by the soil and, thirdly, to calculate the overall inputs and losses of N from the crop–soil system.

MATERIALS AND METHODS

Soil and history of the experimental site

The ^{15}N experiments were made on section 1 of the Broadbalk Wheat Experiment at Rothamsted Experimental Farm on soil classified as Batcombe series (Avery & Bullock, 1969). The topsoil (about 0–23 cm) is a flinty clay loam to silty clay loam containing about 28% clay, 51% silt, 14% fine sand and 6% coarse sand. This overlies clay with flints containing at least 50% clay; the ^{15}N experiments extended over two slightly different subsoil variants. Chalk occurs at 2 m or more and the almost level site is freely drained. The topsoil contains about 1% organic carbon, 0·1% total N, 2% free $CaCO_3$, has a pH of 7·5–8·0 and a cation exchange capacity of 16 m-equiv/100 g.

The Broadbalk experiment was started in 1843 on a field which had been in cultivation for at least two centuries, and probably much longer. Wheat has been grown every year on section 1, except for the period 1925–66 when it was bare fallowed 1 year in 5 to control weeds; since 1966 weeds have been controlled by weedkillers. Fertilizer treatments have been almost unchanged since 1856. Full details of past treatments are given by Johnston & Garner (1969) and Dyke *et al.* (1983).

Plots 5, 6, 7, 8 and 9 receive 0, 48, 96, 144 and 192 kg N/ha per year, together with P, K and Mg. These plots are referred to as N_0, N_1, N_2, N_3 and N_4 respectively. Each plot has been given the same annual application of N since 1852, except plot 9 which has received 192 kg N/ha per year since 1968: previously it received 48 kg N/ha per year as sodium nitrate. Nitrogen is now applied as a single dressing of 'Nitro-Chalk' (ammonium nitrate–calcium carbonate) in April. Plot 10 receives 96 kg N/ha per year but no P, K or Mg, providing a contrast with plot 7, which receives the same rate of N but adequate P, K and Mg. During the period of the present work plots 15 and 16 received the same rates of N as plots 8 and 7 respectively. Details of field operations are shown in Table 1; further information is given in 'Yields of the Field

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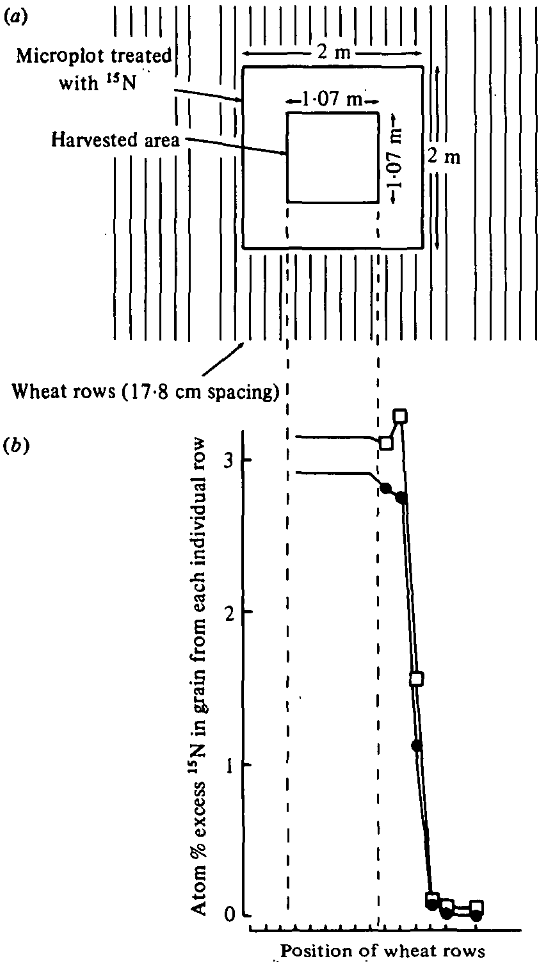

Fig. 1. (*a*) Position of microplots and harvest area in relation to wheat rows. (*b*) Edge effects measured in 1980. □—□, $K^{15}NO_3$ applied; ●—●, $(^{15}NH_4)_2SO_4$ applied.

Experiments' (Rothamsted Experimental Station, 1980–3).

Application of ^{15}N*-labelled fertilizer*

Six microplots, each 2 × 2 m, and spaced at 2 m intervals, were sited along the centre line of plots 6, 7, 8, 9 and 10. These spanned the 12 central wheat rows as shown in Fig. 1(*a*). In April 1980 three of the six microplots within each Broadbalk plot were covered when the unlabelled N fertilizer was broadcast. The covers were removed and the microplots then given ^{15}N-labelled fertilizer at the appropriate rate. In April 1981 the other three microplots were used. On all other occasions the microplots received unlabelled 'Nitro-Chalk' at the normal rates. Six microplots were similarly sited on plot 5, but received no N. ^{15}N-labelled fertilizer, nominally at 144 kg N/ha, was applied to three further microplots in the discard areas of plots 8 and 9 in 1982 and 1983 respectively; plot 9 normally receives 192 kg N/ha.

There were also two subsidiary experiments. The first was an unreplicated experiment comparing NH_4^+ and NO_3^- as sources of N and was made in 1980 and 1981 on microplots established on plots 15 (N_3) and 16 (N_2) of the main experiment. The second, made in 1981, was located in the discard areas of plot 5; it was designed to see whether the addition of fertilizer N increased the uptake of soil N.

Labelled fertilizer was applied to plots 6, 7, 8, 9 and 10 as a solution containing equal amounts of NH_4-N (as $(^{15}NH_4)_2SO_4$) and NO_3-N (as $K^{15}NO_3$) using a spreader designed to give accurate and even application (Woodcock *et al.* 1982). The ^{15}N enrichments of the fertilizers were 4·874, 4·851, 4·683, and 1·980 atom % excess in 1980, 1981, 1982 and 1983 respectively, atom % excess being defined as (measured atom % $^{15}N - 0{\cdot}3663$). On plots 15 and 16, one microplot received N entirely as $(^{15}NH_4)_2SO_4$ (at 4·901 and 4·813 atom % excess in 1980 and 1981 respectively) and one as $K^{15}NO_3$ (at 4·851 and 4·822 atom % excess in 1980 and 1981 respectively) but at the rate of N appropriate to the main plot.

The amounts of labelled fertilizer applied were within 3% of the nominal value for each plot, except in 1980 when an earlier and less accurate version of the spreader was used (see Table 4). Recoveries of fertilizer N are all calculated on the actual amounts of ^{15}N-labelled fertilizer applied.

After applying the labelled fertilizer solution, each plot was watered with 2 l of distilled water from a watering can to wash labelled fertilizer off the wheat plants and on to the soil. To check the effectiveness of this treatment, some plants were sampled from plot 8 in 1982, 2 h after 142·5 kg labelled N/ha had been applied and watered in. The plants were at growth stage 22, with an average height of 15 cm. Only 2·1 kg labelled N/ha remained on the plants, 1·5% of that applied.

Crop and soil sampling

At time of ^{15}N *application*

Small samples of crop and soil were taken in spring, immediately before application of ^{15}N. Plants were pulled by hand from two 0·5 m lengths of row just inside the edge of each 2 × 2 m microplot. Loose soil was returned to the microplot and the plants subsequently washed free of soil in an ultrasonic cleaning tank before being dried at 80 °C. This sample included the above-ground parts, the crown and a small amount of root.

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Two soil cores (4·75 cm diameter and 23 cm deep) were taken from the edge of each microplot. Deeper cores (23–60 and 60–100 cm) were taken from the spaces between microplots on plots 5 and 9 only. The soil cores were stored frozen and, after thawing, sieved (< 6·25 mm) and extracted with KCl for determination of inorganic N.

At harvest

Plants were cut 5 cm above ground level from 1·07 m lengths of 6 adjacent rows in the centre of each microplot (Fig. 1*a*). Samples of stubble (including the crown, just below the soil surface) were taken from a 1·07 m length of row adjacent to the harvested area and adhering soil removed as described above.

There were many weeds (mainly horsetails, *Equisetum arvense* L., which are resistant to the weedkillers currently used on Broadbalk) on plot 5 and some on plots 6 and 10, i.e. those plots where there was least competition from the wheat. These were harvested in all years except 1980. Weeds were negligible on all other plots.

Soil samples were taken with a petrol-driven post-hole screw auger (Sachs Dolmar Earth Borer model 309) immediately after harvest from within the harvest area of each microplot, after first removing the stubble. The plough layer (0–23 cm) was sampled with a 30 cm diameter auger, which passed through a steel plate on which the soil was collected. For deeper horizons, a 15 cm auger was used, after placing a liner in the existing 30 cm diameter hole to ensure that subsoil samples were not contaminated with the more highly enriched topsoil.

In 1980 sampling was restricted to the plough layer because the plots were subsequently to be used for measurements of the uptake of residual ^{15}N and it was thought that deep sampling might alter the drainage characteristics of the soil. In other years deeper samples (23–50 and 50–70 cm) were taken from some plots.

Two holes were drilled within the harvest area of each microplot. Soil from the two holes was bulked, sieved (< 25·4 mm), and the soil and stones weighed. A 2 kg subsample was taken and the remainder of the soil returned to the hole, together with the stones and stubble. In the case of subsoils, a 0·7 kg subsample was taken, the remaining soil returned to the hole and packed to its original volume.

The soil samples were stored at 2 °C for up to 1 week and then sieved (< 6·25 mm), weighed and further subsampled. A 500 g subsample was air-dried and then ground in a disk mill (Tema model T100) for measurement of total N and ^{15}N.

Sample preparation

Grain, chaff and straw were separated in a single-ear thresher. Subsamples (about 100 g grain, 30 g chaff, 30 g chopped straw and the whole of the stubble sample) were dried at 80 °C for 18 h and ground in a disk mill (Tema model T100), which was washed between samples to eliminate cross-contamination.

Dry weights and N contents of grain, chaff, straw, stubble and weeds are expressed on an oven-dry (80 °C) basis, apart from the grain yields in Tables 3 and 4 which are expressed at 85% dry matter. Analyses of soil were done on the air-dry material but results are expressed on the basis of oven-dry (105 °C) weight, which was determined on a separate subsample. The weight of oven-dry < 6·25 mm soil per ha in each soil layer was calculated for each microplot. There were no systematic trends in soil weights from year to year, nor were there any significant differences between plots, so the following mean soil weights were used to calculate the contents of labelled and unlabelled N in soil: $2·61 \times 10^6$ kg/ha (0–23 cm layer), $3·43 \times 10^6$ kg/ha (23–50 cm) and $2·62 \times 10^6$ kg/ha (50–70 cm).

Analytical methods

Total N was determined in plant and soil samples using the salicylic acid modification of the Kjeldahl method to include nitrate-N (Bremner, 1965*a*). $^{14}N/^{15}N$ ratios were measured on a VG Micromass model 602D mass spectrometer: details of the analytical methods are given by Pruden, Powlson & Jenkinson (1985).

Soil samples taken just before N fertilizer application were extracted with KCl (300 g moist soil shaken with 1 l 2 M-KCl for 30 min) and NH_4-N and NO_3-N were measured in the filtered extract by steam distillation with MgO followed by Devarda's alloy (Bremner, 1965*b*).

RESULTS

Crop sampling and edge effects

In 1980 some extra plant samples were taken from outside the six-row harvest area to test whether the 0·5 m discard (three rows of plants, Fig. 1*a*) was sufficient to prevent plants within the harvested area absorbing unlabelled fertilizer from outside the microplots. Figure 1(*b*) shows the atom % excess of grain from the sampled rows for plots given ^{15}N-labelled NH_4-N or NO_3-N separately. The results show that a 3-row discard was adequate; even if the discard had been reduced to two rows the resulting decrease in the ^{15}N enrichment of the harvested grain would have been less than 2%. In 1981, a wetter year, similar results were obtained,

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Table 2. *Total N in wheat and inorganic N in soil at time of application of fertilizer N*

Year	Plot no.	Treatment code	Annual N application (kg N/ha)	Crop dry weight at time of N application* (t/ha)	Crop N content at time of N application (kg N/ha)	(NH_4+NO_3)-N in soil at time of application (kg N/ha)		
						0–23 cm	23–60 cm	60–100 cm
1980	5	N_0	0	0·66	13·0	14·0	18·2	9·0
	6	N_1	48	0·66	13·3	14·5	—	—
	7	N_2	96	1·31	29·1	12·9	—	—
	8	N_3	144	1·41	31·7	16·1	—	—
	9	N_4	192	1·61	38·2	14·4	11·7	10·4
	10	N_2 (no P, K or Mg)	96	0·36	11·3	8·5	—	—
1981	5	N_0	0	0·86	20·3	7·7	14·7	13·1
	6	N_1	48	1·02	24·5	3·4	—	—
	7	N_2	96	1·68	42·9	2·1	—	—
	8	N_3	144	1·87	51·5	5·3	—	—
	9	N_4	192	1·90	50·8	4·4	12·8	17·1
	10	N_2 (no P, K or Mg)	96	0·74	24·8	2·0	—	—
1982	5	N_0	0	0·37	7·8	—	—	—
	8	N_3	144	0·58	13·4	11·0	—	—
1983	9	N_3	144†	0·48	11·3	—	—	—
	8	N_0	0‡	0·52	12·8	—	—	—

* 11 April 1980, 13 April 1981, 16 April 1982 and 15 April 1983.
† Discard area of plot 9. Normally receives 192 kg N/ha but given 144 kg N/ha in 1983 only.
‡ Discard area of plot 8. Normally receives 144 kg N/ha but given no N in 1983 only.

although enriched N did spread a little further than in 1980.

Recovery of increasing applications of fertilizer nitrogen by crops given adequate P, K and Mg

Nitrogen in crop and soil at time of fertilizer application

When sampled in April, before the fertilizer N was applied, wheat growing on plots that received high rates of N annually was always larger, and contained more N, than wheat from low N plots (Table 2). For example, in April 1980 wheat given 192 kg N/ha each year (N_4) contained three times as much N as that given no fertilizer N; in 1981 there was a two-fold difference. In April 1981 the plants were larger, and had taken up more N, than at the corresponding time in 1980. There was less inorganic N in the topsoil (0–23 cm) at this time in 1981 so that, for each plot, the sum of N in crop

Table 3. *Grain yields (t/ha, 85% D.M.) calculated from combine harvested areas (79·8 m^2) and from hand harvested areas within ^{15}N microplots (mean of three sample areas, each 1·14 m^2)*

Treatment code	1980		1981		1982		1983	
	Combine	^{15}N plots	Combine	^{15}N plots	Combine	^{15}N plots	Combine	^{15}N plots
N_0	1·49	1·44	1·62	1·45	1·10	1·13*	1·50	1·54
N_1	3·74	3·20	4·28	4·23	3·36	—	3·52	—
N_2	6·25	5·61	6·39	6·53	5·47	—	5·36	—
N_3	7·17	6·56	6·36	6·33	5·76	6·05*	5·78	5·89
N_4	7·56	7·32	6·96	6·45	6·60	—	6·37	—
N_2 (no P, K or Mg)	3·69	3·60	3·72	3·78	2·78	—	3·03	—

* Corrected for grain in chaff; see Appendix Table 1.

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Table 4. *Uptake of labelled and unlabelled N by wheat and retention of labelled N in soil*

Year and plot no.	Treatment code	^{15}N-labelled fertilizer applied (kg N/ha)	Grain yield (t/ha, 85 % D.M.)	N in crop (grain, chaff, straw and stubble) (kg N/ha)			Labelled N remaining in soil after harvest (kg N/ha)			Percentage recovery of fertilizer N			
				Labelled	Unlabelled	Total	0–23 cm	23–50 cm	50–70 cm	In grain	In above ground crop	In soil (0–23 cm)	In crop + soil (0–23 cm)
1980													
5	N_0	0	1·44	0	30·1	30·1	—	—	—	—	—	—	—
6	N_1	47·3	3·20	23·9	39·9	63·8	16·9	ND	ND	42	51	36	86
7	N_2	94·4	5·61	60·4	61·0	121·3	17·4	ND	ND	52	64	18	82
8	N_3	141·0	6·56	96·3	74·3	170·6	24·0	ND	ND	55	68	17	85
9	N_4	181·6	7·32	121·3	75·6	196·9	25·2	ND	ND	53	67	14	81
10	N_2 (no P, K or Mg)	87·7	3·60	40·3	52·7	93·0	28·5	ND	ND	38	46	32	78
	S.E.[a]		0·184	2·80	2·07	4·16	1·19	—	—	1·9	2·3	1·1	2·3
1981													
5	N_0	0	1·45	0	30·9	30·9	—	—	—	—	—	—	—
6	N_1	49·3	4·23	25·6	50·0	75·6	14·6	0·8	0·2	40	52	30	82[b,c]
7	N_2	97·5	6·53	59·6	72·6	132·2	22·7	ND	ND	46	61	23	84
8	N_3	147·4	6·33	78·6	73·2	151·7	29·8	ND	ND	37	53	20	74
9	N_4	195·8	6·45	111·9	71·7	183·7	31·7	5·8	0·9	38	57	16	73[d]
10	N_2 (no P, K or Mg)	98·8	3·78	38·5	45·1	83·6	24·3	ND	ND	30	39	25	64[e]
	S.E.[a]		0·245	2·76	4·41	5·50	2·10	0·16	0·09	1·5	2·0	1·9	3·4
1982													
5	N_0	0	1·13[f]	0	23·0	23·0	—	—	—	—	—	—	—
8[g]	N_3	142·5	6·05[f]	96·4	52·4	148·8	26·8	4·5	2·0	45	68	19	86[h]
1983													
5	N_0	0	1·54	0	29·2	29·2	—	—	—	—	—	—	—
9[i]	N_3	151·0	5·89	86·9	56·1	143·1	19·1	4·6	ND	44	57	13	70[j]
8[g]	N_0	0	2·65	2·2	49·8	52·0	—	—	—	—	—	—	—

[a] Standard error of means.
[b] Includes 0·3 % in weeds; see Appendix Table 1.
[c] An additional 2 % present in 23–70 cm soil.
[d] An additional 3 % present in 23–70 cm soil.
[e] Includes 0·4 % in weeds; see Appendix Table 1.
[f] Corrected for incomplete separation of grain from chaff in 1982 from the mean (chaff weight)/(grain weight) ratios from the corresponding plots in 1980, 1981 and 1983.
[g] Discard area of plot 8, given N_3 (labelled) in 1982 but no N fertilizer in 1983.
[h] An additional 5 % present in 23–70 cm soil.
[i] Discard area of plot 9 (N_4) given N_3 in 1983 only.
[j] An additional 3 % present in 23–50 cm soil.
ND, not determined.

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plus inorganic N in topsoil was almost the same in the 2 years (Table 2). Crop weights and N contents in spring were lower in 1982 and 1983 than for the corresponding N rates in the other 2 years, probably because the 1982 and 1983 crops were sown later than the 1980 and 1981 crops.

Dry-matter production and grain yield

In all years there was satisfactory agreement between grain yield as measured on the three hand-harvested ^{15}N microplots (total area $3{\cdot}43\ m^2$) and on the combine-harvested area of the main plot ($79{\cdot}8\ m^2$; Table 3). The largest grain yield measured on the ^{15}N microplots was 7·32 t/ha at 85% D.M., given by the N_4 treatment in 1980 (Table 3). In 1980 and 1981, the 2 years in which all rates of N were tested, total dry-matter production ranged from about 3 to more than 13 t/ha (Appendix Table 1).

Labelled fertilizer N in crop and soil at harvest

In 1980 and 1982 the wheat crop recovered about 66% of the labelled fertilizer N applied, the only exception being the N_1 plot in 1980, in which recovery was only 51% (Table 4). When fertilizer N retained in the plough layer soil (0–23 cm) is included, 81–86% of the labelled N can be accounted for at harvest in 1980 and 1982. In 1980 the soil was not sampled to greater depth but in 1982 the 23–70 cm soil layer contained a further 5% of the labelled fertilizer N (Table 4). Thus in 1982, and probably 1980, the loss of fertilizer N from the crop–soil system was only about 10% of that applied.

In 1981 recoveries of fertilizer N in the crop were similar to those in 1980 for the two lower rates of N but were less at the two higher rates, only about 55% being recovered at N_3 and N_4, compared with 68% in 1980. Recovery in crop plus soil (0–23 cm) was only 74% for N_3 in 1981. In 1983, when only N_3 was tested, recovery was also low: 70% in crop plus soil to 23 cm, with a further 3% to 50 cm.

The proportion of fertilizer N remaining in the soil at harvest decreased as application rate increased (Table 4). Thus, of the 47 kg N/ha applied in 1980, 36% was retained; of the 182 kg N/ha applied in the same year, 14% was retained.

At the lowest rate of N (plot 6, N_1) there was a significant growth of weeds (mainly *Equisetum arvense*, as on the N_0 plot) but nearly all of the N in weeds was unlabelled (Appendix Table 1).

Uptake of unlabelled soil-derived N

In 1980 and 1981, crop uptake of unlabelled N at harvest increased from about 30 kg/ha at N_0 to over 70 kg/ha at the highest N rates (Table 4). The difference was less if the N in weeds (9–14 kg N/ha at N_0) was included because weeds were only present on plots given little or no N (Appendix Table 1). Part of this difference between high N and low N plots was already apparent in April (Table 2), before the current year's fertilizer N was applied and before the weeds had appeared. For example, at harvest 1980 the wheat on the N_3 plot contained 44 kg/ha more unlabelled N than that on the N_0 plot, but in April there was already a difference of 19 kg/ha. The amounts of residual inorganic N in the 70 cm depth of soil are small after harvest and unlikely to contribute significantly to the extra unlabelled N in the plots given high rates of fertilizer. However, crops given much N return more organic matter to the soil as roots, root exudates and stubble than crops given little N, so that more organic N accumulates in the soil. Mineralization of N in plots given high rates of fertilizer will therefore be correspondingly large. Appendix Table 1 shows that the amount of stubble (ploughed into the soil after harvest) increases with rate of N application; there was more than twice as much stubble on plot 9 (N_4) as on plot 5 (N_0). Appendix Table 1 also shows that total soil N increases somewhat with increasing applications of fertilizer N, with the exception of plot 9. Plot 9 (N_4) contains less total N than plot 8 (N_3) and the uptake of unlabelled N by the crop was no greater than on plot 8 (Table 4). The explanation of this anomaly is that plot 9 received only 48 kg N/ha (N_1) until 1968, so for much of its history the annual return of plant residues, and retention of N, were much less than in plot 8.

Comparison of the total N uptake by the crop grown in 1983 on plot 5, which never received N, and on the discard area of plot 8, which received N every year except in 1983, gives a direct measure of the effects of fertilizer history on the supply of N from the soil. The wheat on plot 8 contained 52 kg N/ha; that on plot 5 29 kg/ha, plus a further 9 kg/ha in weeds (Table 4 and Appendix Table 1). This is further evidence that soils with a long history of receiving N fertilizer, and greater returns of crop residues, contain more mineralizable N.

Uptake of unlabelled N on plot 8 (N_3) varied from year to year, ranging from 74 kg/ha in 1980 to 52 kg/ha in 1982 (Table 4). These differences were already apparent in the total N contents of the crop at the time of fertilizer application in April (Table 2). They probably reflect the different sowing dates in the 4 different years, the 1982 and 1983 crops being sown later than the others (Table 1). Inorganic N not taken up by the late-sown crops in autumn would have been leached out of the soil during winter (Widdowson, Darby & Bird, 1982).

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Table 5. *Effects of ^{15}N-labelled fertilizer on uptake (kg N/ha) of unlabelled N by plants in* 1981

^{15}N-labelled fertilizer applied	N in wheat (grain, chaff and straw)			N in weeds			Unlabelled N in wheat plus weeds
	Labelled	Unlabelled	Total	Labelled	Unlabelled	Total	
None	0	28·7±1·4	28·7±1·4	0	13·4±0·6	13·4±0·6	42·1±1·4
149·1	70·0±3·0	37·9±0·6	107·9±3·6	0	0	0	37·9±0·6

Table 6. *Percentage recovery of fertilizer N in grain plus straw as calculated by difference and by ^{15}N recovery*

Treatment code	1966–7 Subtracting plot 5	1970–8 Subtracting plot 5	1980 Subtracting plot 5	1980 ^{15}N recovery	1981 Subtracting plot 5	1981 ^{15}N recovery
N_1	32	56	65	46	82	47
N_2	39	63	90	59	93	54
N_3	36	59	93	64	71	47
N_4	—	52	84	62	67	50

Interactions between soil N and fertilizer N

Fertilizer N can, in certain circumstances, stand proxy for soil N that otherwise would have been immobilized. If labelled fertilizer is used, the effect of this process is to cause an apparent increase in the amount of soil (i.e. unlabelled) N taken up by a crop (Jenkinson *et al.* 1985). This increase in uptake of soil N is described as a positive apparent 'added nitrogen interaction' (ANI). However, a large positive apparent ANI is unlikely in these experiments, in which fertilizer N was applied to the soil surface and not mixed with the soil, and indeed an apparent ANI could arise only through interaction between labelled fertilizer and that part of the soil N taken up by the crop after application of fertilizer. Nevertheless, two experiments were made to test for such an effect, one in 1981 and another in 1983.

In 1981, ^{15}N-labelled fertilizer (149·1 kg N/ha), applied to three microplots on plot 5, increased the uptake of unlabelled N by 9 kg/ha (Table 5). The weeds on the microplots given N contained less than 1 kg N/ha but where no N was given they contained 12 kg N/ha. If it is assumed that soil-derived N was equally available to both wheat and weeds, then the results in Table 5 indicate that no ANI occurred in 1981. If, on the other hand, none of the N taken up by weeds was available to the wheat, the addition of fertilizer N caused a positive ANI of, at most, 9 kg/ha.

The second experiment was made in 1983 on parts of plots 8 and 9, where mineralization of soil N is now the same: see Table 4 for the uptakes of unlabelled N from these plots in 1980 and 1981. Labelled fertilizer was applied at the N_3 rate to microplots on plot 9, whereas microplots on plot 8 that had received labelled fertilizer in 1982 received no fertilizer N in 1983. The results (Table 4) which are not complicated by the presence of weeds, show that there was no measurable ANI in 1983. Wheat given labelled fertilizer (151 kg N) took up 56 kg/ha of unlabelled N, whilst that given no N obtained 52 kg N/ha from the soil, of which 2·2 kg/ha was from the residue of the labelled N applied in the previous year.

In both 1981 and 1983 considerable rain fell shortly after fertilizer application. This would have increased the degree of mixing of labelled and unlabelled inorganic N and so increased the opportunity for an ANI to occur (Jenkinson *et al.* 1985). The other 2 years of the experiment were drier, so it is safe to conclude that ANIs were negligible in all 4 years of these experiments.

Calculation of crop recovery of fertilizer nitrogen

Crop recoveries calculated by the difference method, i.e. by subtracting the N offtake of the crop not given fertilizer N (plot 5), are all greater than those calculated by the ^{15}N method (Table 6). This is because soils not given N fertilizer for many years contain much less mineralizable organic N than soils given N regularly. Where a true control was available (on plot 8 in 1983, see previous section), there was reasonable agreement between recoveries calculated by subtraction of control (57%) and by uptake of labelled fertilizer (54%).

Recoveries calculated by difference from some earlier periods (Dyke *et al.* 1983) are also given in Table 6. Although the recoveries calculated by subtracting the N offtake of plot 5 are too large, they are all calculated on the same basis and do indicate

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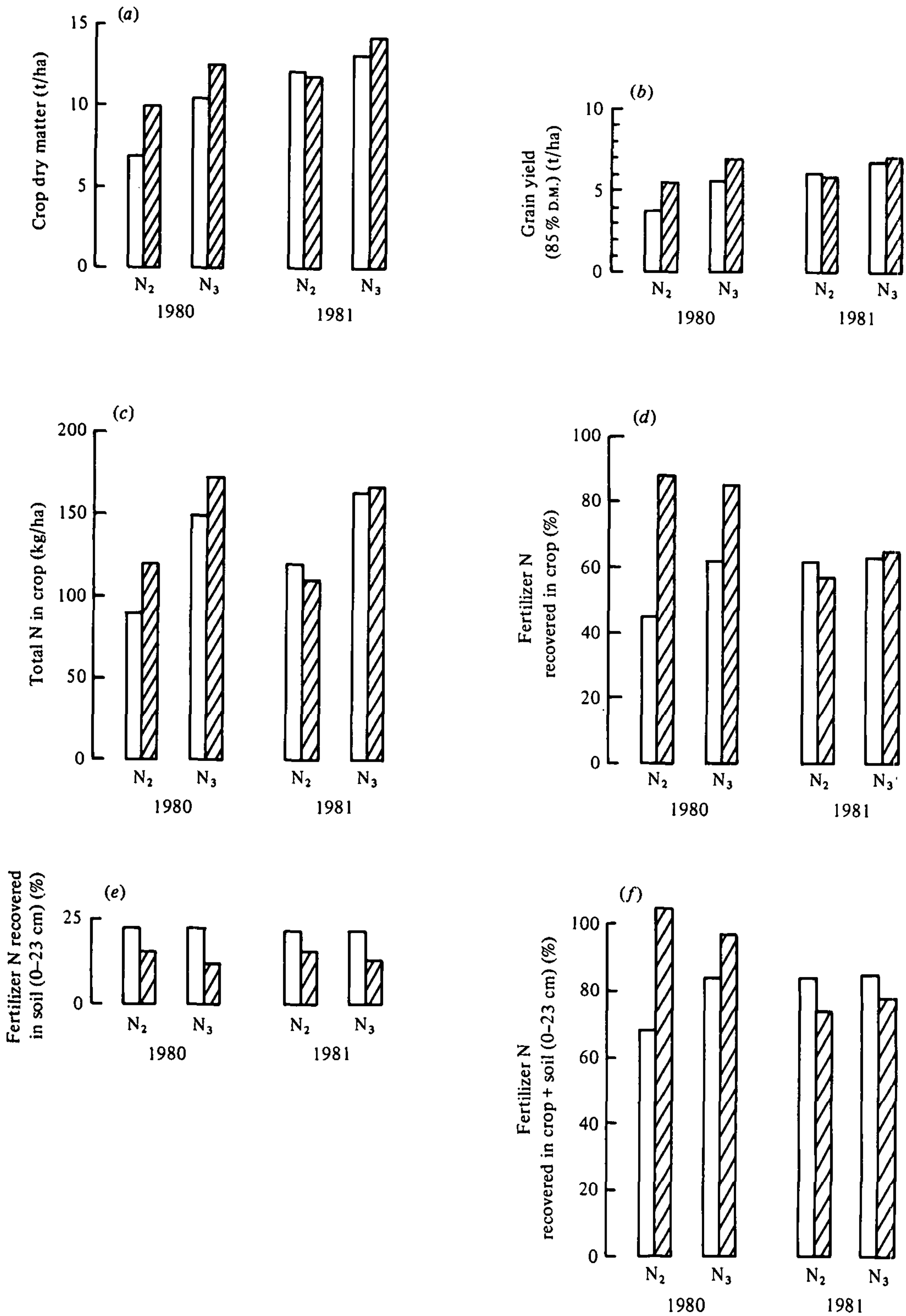

Fig. 2. Comparative effects of ^{15}N-labelled ammonium- and nitrate-N on crop growth, N uptake and recovery of fertilizer N. □, $(^{15}NH_4)_2SO_4$ applied; ▨, $K^{15}NO_3$ applied.

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how the efficiency of use of N fertilizer has changed since 1966. Recoveries since 1980 are all greater than those in earlier periods because of the much larger yields and N offtakes on plots given N. These, in turn, resulted from changes in wheat variety in 1968 and 1978, and from improvements in pathogen control (see Dyke *et al.* 1983). The offtake of N from plot 5 changed little between 1852 and 1983, so that the increased recoveries calculated by the difference method are not caused by a decreased uptake of N by the control.

Uptake of nitrogen by phosphate-deficient wheat

Dry-matter production, grain yield and total N uptake

Plot 10 receives the same annual application of N as plot 7 (96 kg N/ha) but no P, K or Mg. The yield on plot 10 is much smaller than on plot 7, mainly because of severe P deficiency; 0·5 M-$NaHCO_3$-extractable P is 7 and 80 mg/kg on plots 10 and 7 respectively. In 1980 and 1981 dry-matter production and grain yield on plot 10 were about 60% of those on plot 7, although the difference in total N uptake was less marked, because % N in grain was greater in plot 10 (Table 4 and Appendix Table 1).

Recovery of labelled fertilizer N in crop and soil

In both 1980 and 1981 crop uptake of fertilizer N was considerably lower on the P-deficient plot 10 than on plot 7 (Table 4). In the dry year of 1980, 32% of the fertilizer N added to plot 10 was recovered in the topsoil at harvest, much more than in plot 7 (18%). Consequently the recovery of fertilizer N in crop plus topsoil was almost the same in both soils. In contrast, recovery in crop and soil was much lower in plot 10 in the wet spring of 1981.

Comparison of ammonium and nitrate as sources of nitrogen for wheat

In 1980 wheat given $(NH_4)_2SO_4$ grew less well than that given KNO_3: both total crop dry matter and N uptake were lower with ammonium-N than with nitrate-N (Fig. 2*a*, *c*). Ammonium gave about 1·5 t/ha less grain than nitrate at both rates of N (Fig. 2*b*) and there was a lower uptake of labelled N from $(NH_4)_2SO_4$ than from KNO_3 (Fig. 2*d*); uptake of unlabelled soil-derived N was unaffected by the form of N applied. In contrast, there was little difference in growth, total N uptake, or uptake of labelled N in 1981 (Fig. 2).

In both years, and at both rates of N, a greater proportion of ammonium- than nitrate-derived N was recovered in the topsoil at harvest (Fig. 2*e*). The soil microbial biomass immobilizes ammonium N in preference to nitrate N (Jansson, 1958) and this additional N was presumably immobilized during the brief period when labelled NH_4^+ was present in the soil of the $(NH_4)_2SO_4$ plot.

In 1980, 100% of the nitrate-derived N could be accounted for in crop plus topsoil at harvest, whereas the corresponding value for ammonium-derived N, averaged over the two rates of application, was only 76% (Fig. 2*f*). In the main experiment, in which N was applied as a mixture of ammonium and nitrate, overall recovery was intermediate (84%, mean of plots 6–9), suggesting that a loss process, presumably ammonia volatilization, occurred in 1980 that affected ammonium N but not nitrate N. In 1981 about 80% of the labelled N could be accounted for, whether applied as ammonium, nitrate or a mixture, so that an ammonium-specific loss process was not important in that particular year. However, a subsidiary experiment on ammonia volatilization, made in April 1981, showed that there was some loss, even in that year. Immediately after applying ^{15}N-labelled fertilizer, two petri dishes containing H_2SO_4 were placed on the surface of the $(NH_4)_2SO_4$ and KNO_3 plots; each was covered with a metal drum (35 cm diameter and 10 cm high) pressed into the soil. The average amount of NH_3 evolved during the next 24 h from the $(NH_4)_2SO_4$ plots was equivalent to 0·03 kg N/ha; none was detected from the KNO_3 plots. These measurements suggest that some NH_3 volatilization can occur when ammonia-containing fertilizer is applied to the surface of this soil at pH 8. In the wet spring of 1981 this loss, although measurable, was small but in the drier conditions of 1980 it may well have been substantial.

DISCUSSION

Efficiency of use of nitrogen fertilizer

These results show that spring-applied nitrogen fertilizer can be used very efficiently by winter wheat grown in monoculture, above-ground crop recoveries of up to 68% being obtained in 2 of the 4 years. These recoveries (Table 4) were mostly higher than those measured by Leitch & Vaidyanathan (1983) in an experiment on a Hanslope Series clay soil. They found that between 30 and 50% of labelled fertilizer N was recovered by winter wheat and overall recovery in crop plus soil ranged from 55 to 75%, depending on the method of cultivation and the rate and time of N application. Dowdell & Crees (1980) measured 60–68% recovery of labelled fertilizer N by winter wheat confined within PVC tubes inserted into an Evesham Series clay soil. Recoveries in the Broadbalk experiment were similar to those in Kansas, in which $(^{15}NH_4)_2SO_4$ was applied to winter wheat grown on a silt loam soil (Olson *et al.* 1979) and to those obtained with $^{15}NH_4{}^{15}NO_3$ in Belgium (Van Cleemput & Baert, 1984). In several experiments with spring-sown barley, either in lysimeters (Dowdell *et al.* 1984; Kjellerup & Dam Kofoed,

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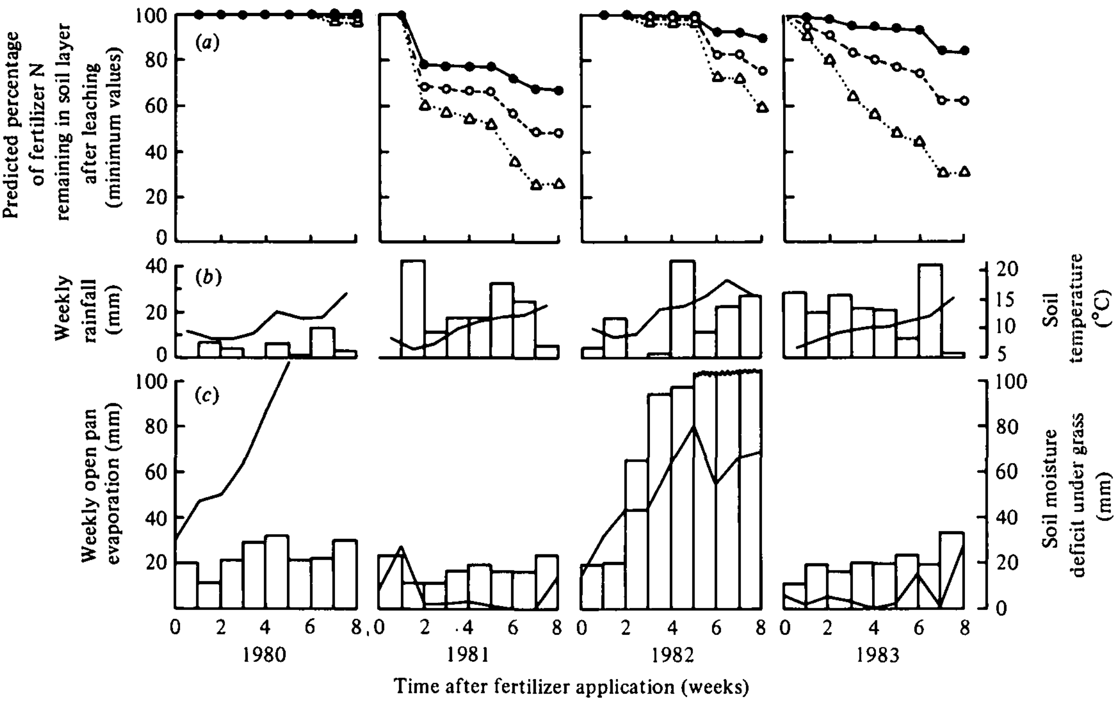

Fig. 3. (*a*) Predicted percentage of fertilizer N remaining in different soil layers (●——● 0–90 cm; ○- - -○ 0–50 cm; △. . . .△ 0–25 cm) assuming that all fertilizer N was applied as nitrate and that leaching was the only process removing nitrate from soil. (*b*) Weekly rainfall (histograms) and weekly mean soil temperature, measured at 20 cm under grass at 09.00 h G.M.T. (——). (*c*) Soil moisture deficit under grass (——) and weekly open pan evaporation (histograms). All are shown for the 8-week period following fertilizer application.

1983) or in field plots (Smith *et al.* 1984), crop recovery of labelled fertilizer N tended to be lower than was measured for winter wheat on Broadbalk; values ranged from less than 30% in some cases (Smith *et al.* 1984) to 57% (Kjellerup & Dam Kofoed, 1983). With autumn-sown barley, recoveries were higher (Smith *et al.* 1984; Khanif, Van Cleemput & Baert, 1984). It is likely that the root system of a spring-sown crop, which develops later, will be less effective at absorbing spring-applied N than that of an autumn-sown crop.

In 1981 overall losses from the crop–soil system were greater with larger than with smaller applications (Table 4), presumably because larger additions were at risk over a longer period. Ignoring immobilization, and taking the rate of uptake of N by winter wheat during the period of stem extension to be 3 kg N/ha per day (Gregory, Crawford & McGowan, 1979; Prew *et al.* 1983), 48 kg of fertilizer N would be taken up in 16 days, but 64 days would be needed for 192 kg.

The major factor determining loss of N from the larger applications of fertilizer was weather. In 1980 and 1982, when spring rainfall was low, and a substantial soil moisture deficit built up, losses were small. In 1981 and 1983, when spring rainfall was high and soil moisture deficits remained very small throughout April and May (Fig. 3*b*, *c*), losses were large. Addiscott's (1977) model for leaching in structured soils was used to see whether leaching alone could account for the measured loss of fertilizer N. If the predicted leaching loss, calculated using assumptions that will tend to overestimate leaching, is less than the total loss, then denitrification is implicated. Figure 3 shows the predicted percentage of the fertilizer N remaining in the 0–25, 0–50 and 0–90 cm soil layers based on the following assumptions: (*a*) that all fertilizer N was applied as nitrate (in fact it was applied as 50% nitrate and 50% ammonium in the main experiments); the ammonium would have to nitrify before it could be subject to leaching; (*b*) that leaching was the only process affecting the quantity of nitrate in soil, no allowance being made for the removal of nitrate from soil by crop uptake or immobilization; (*c*) that any nitrate within

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90 cm of the soil surface will be available to the crop. Root studies at Rothamsted (Barraclough & Leigh, 1984) show that the roots of autumn sown cereals normally extend to a depth of at least 1 m by April.

The model predicts that 100 and 92% of the fertilizer N was still present in the top 90 cm of soil 6 weeks after addition in 1980 and 1982, respectively (Fig. 3*a*). The small losses measured in the ^{15}N experiments in 1980 and 1982 (about 10%, Table 4) are therefore most unlikely to have been caused by leaching. Denitrification and NH_3 volatilization are the most likely processes involved. In 1983 the model suggests that there was significant movement of nitrate down the soil profile but even in that year 93% of the fertilizer N remained within the 0–90 cm layer after 6 weeks (Fig. 3*a*). It is therefore most unlikely that leaching could account for the 25% loss of fertilizer N measured with ^{15}N in 1983; denitrification almost certainly made the major contribution. However, leaching may have made an appreciable contribution to the loss of N in 1981. There was 42 mm of rain in the 2nd week after fertilizer application and the model predicts that this caused 22% of the N to be leached below 90 cm. The experiment with ^{15}N indicated a loss of about 24% for N_4 in 1981 (Table 4).

Even when losses of N were small, only about half of the labelled fertilizer N was recovered in grain (Table 4). Opportunities for increasing the proportion recovered in grain rather than in other parts of the crop–soil system are limited, although a further increase in the harvest index of wheat would increase the proportion in grain.

Total N contents of Broadbalk soils

The continued application of fertilizer N has had a rather small effect on soil N content. For example, plot 8 (N_3) has received about 20 t fertilizer N/ha since 1843, yet this plot contains only some 600 kg/ha more N in the 0–23 cm soil layer than plot 5 (Appendix Table 1; mean of 1980 and 1981 measurements). This represents an overall retention of the applied fertilizer N of less than 3%, assuming that the soil N contents of plots 5 and 8 were equal at the beginning of the experiment.

These results also show that the total N content of a soil is a poor indicator of its capacity to mineralize nitrogen. The total uptake of soil-derived N by plants on plot 8 (containing 3340 kg/ha total soil N) was 73 kg/ha, almost twice the 43 kg/ha taken up from plot 5 (containing 2930 kg soil N; see Appendix Table 1; 1981 results). Thus the relatively small amount of extra N retained in the soil as a result of applying N fertilizer for 140 years made a disproportionately large contribution to the mineralization of N by the soil.

Nitrogen balance for the Broadbalk experiment

The total N contents of the soils in plots 5, 6, 7, 8 and 10 have been virtually constant for at least 100 years (Jenkinson, 1977; Johnston, 1969) and can therefore be taken to be under steady state conditions, with the quantity of organic N formed each year balanced by the quantity decomposed. Current offtakes of N in grain and straw are now similar to, and sometimes greater than, the amount of N supplied as fertilizer (Table 4; Dyke *et al.* 1983, Table 15). It is therefore necessary to postulate an additional input of N, from sources other than fertilizer, to maintain steady-state conditions. The magnitude of this input can be calculated if the measured values for loss of labelled fertilizer N are used to estimate losses of non-fertilizer derived N. Let:

F = annual input of N from fertilizer
I = annual input of N from non-fertilizer sources
H = N removed annually in harvested part of crop (taken to be grain and straw)
L = annual loss of N from crop–soil system
S = annual release of N from soil organic N (= annual input of N to soil organic N if soil organic N is under steady-state conditions).

All values in kg N/ha per year, the year being assumed to run from one harvest to the next.

Consider a compartment containing the nitrogen in the crop–soil system, but excluding that in the soil organic matter. For steady-state conditions, annual inputs of N to this compartment equal annual outputs of N,

i.e. $$F+I+S = H+L+S. \qquad (1)$$

Let x be the fraction of the total annual input (i.e. $F+I+S$) retained in the crop–soil system. Then

$$L = (1-x)(F+I+S). \qquad (2)$$

Let y = the fraction of the total annual input retained in the soil, including that in roots, chaff and stubble. N in chaff is included as most of the chaff is returned to the soil when crops are combine harvested. Then

$$S = y(F+I+S). \qquad (3)$$

From equations (2) and (3)

$$L = \frac{(1-x)(F+I)}{(1-y)}. \qquad (4)$$

From equations (1) and (4)

$$F+I+S = H+\frac{(1-x)(F+I)}{(1-y)}+S.$$

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Table 7. *Nitrogen balance for Broadbalk continuous wheat*, 1979–83*

Harvest year†	Plot no.	Treatment code	Fertilizer N applied (F) (kg N/ha)	N removed in grain and straw (H) (kg N/ha)	y_s	x_s	Calculated input of non-fertilizer N (I) (kg N/ha per year)	Calculated total loss of N (L) (kg N/ha per year)
1980	5	N_0	0	26·4	—	—	34·5‡	8·1‡
	6	N_1	47·3	57·3	0·40	0·86	27·0	17·0
	7	N_2	94·4	111·1	0·23	0·83	49·1	32·4
	8	N_3	141·0	157·6	0·22	0·85	52·9	36·3
	9	N_4	181·6	179·6	0·19	0·81	54·1	56·2
1981	5	N_0	0	26·7	—	—	35·7‡ (53·2)§	10·4‡ (15·5)§
	6	N_1	49·3	67·2	0·35	0·81	45·6	27·7
	7	N_2	97·5	116·9	0·30	0·84	53·4	34·0
	8	N_3	147·4	131·7	0·27	0·74	57·8	73·6
	9	N_4	195·8	158·8	0·23	0·74	46·0	83·1
1982	8	N_3	142·5	135·8	0·24	0·86	23·1	29·8
1983	9	N_3	151·0	133·1	0·16	0·70	56·6	74·5
Mean of 4 years for		N_3	145·5	139·6	0·22	0·79	47·6	53·6

* F, H, y_s, x_s, L and I defined in text.
† Year ends at harvest.
‡ Values of L and I for plot 5 (N_0) calculated using values of y_s and x_s from plot 6 (N_1).
§ Values of L and I in parentheses calculated by including N in weeds in H.

Solving for I,

$$I = \frac{H(1-y)}{(x-y)} - F. \tag{5}$$

Approximate values for y and x can be obtained from the experiments with labelled fertilizers by assuming, first, that the fertilizer input (F), non-fertilizer input (I) and soil input (S) all behave alike and, secondly, that the measured recovery of fertilizer N over the April–harvest period is the same as if it had been measured over the whole year. Making these assumptions, then $y = y_s$, where y_s is the fraction of the labelled N, applied in spring, that is recovered in soil (0–23 cm), stubble and chaff at harvest. Likewise, $x = x_s$, where x_s is the fraction of the labelled N, applied in spring, that is recovered in soil, stubble, chaff, straw and grain at harvest.

Table 7 shows values calculated from equation 5 using these approximations for x and y. The average input for plot 8 (N_3) over 4 years is 48 kg N/ha per year. Apart from the low value in 1982 (a result of the exceptionally high recovery of fertilizer N in that year), values for the different years are in the range 30–60 kg N/ha per year, with no consistent relationships between input of non-fertilizer N and quantity of fertilizer N applied. Wide variation between years is to be expected as the steady-state condition applies only over a run of years: in any particular year, inputs and outputs may well be out of balance. The calculations for plot 5, which receives no fertilizer N, were made using values for x_s and y_s taken from a different plot (plot 6, receiving 48 kg N/ha per year); the results for plot 5 should therefore be treated with caution.

The second of the assumptions made in calculating non-fertilizer N input, that little of the labelled N remaining in soil, stubble and chaff at harvest is lost during the succeeding 8 months, is not greatly in error. Very little labelled inorganic N was present in soil at harvest and, of the total labelled N present in soil, stubble and chaff at the 1980 harvest, 78–90% was still in the soil at the 1981 harvest, a year and 4 months after the original application of labelled fertilizer (Hart *et al.* 1982).

The other assumption, that N derived from different sources (F, I and S) behaves similarly in soil, is less well established. Consider, for example, the supply (S) of N from soil organic matter. Over the year, some is released between harvest and the following April and the rest between April and the next harvest. Values of y_s (or x_s) obtained from experiments with labelled fertilizer applied in spring are clearly more relevant to that part of S released during the April–harvest period than to that released over the preceding winter period, when losses may well have been greater. Powlson *et al.* (1986) found that when 45·4 kg of labelled N (as $K^{15}NO_3$) was added to Broadbalk in October 1980,

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only 54% was recovered in crop plus soil (0–23 cm) at harvest in the following year, compared with a recovery of 82% from 49·3 kg N added in spring 1981 (Table 4). The results from this experiment can be used to see how the less efficient use of mineral N over the winter months affects the calculated value of I. Let $x_w(=0{\cdot}54)$ be the fraction of the labelled N applied in autumn that is recovered in grain, straw, chaff, stubble and soil at harvest 10 months later and $y_w(=0{\cdot}269)$ be the fraction recovered in chaff, stubble and soil; the corresponding values for N applied in spring 1981 (Table 7) are $x_s(=0{\cdot}81)$ and $y_s(=0{\cdot}35)$. Using x_w and y_w for the period harvest–April and x_s and y_s for the period April–harvest, and assuming that one third of $I+S$ is released during the winter period and the remaining two-thirds (plus all of F) between April and harvest, then the calculated value of I is 58·9 kg N/ha per year. If half of I and S is released during the winter and half during the summer, the calculated value of I becomes 67·2 kg. For comparison, the value of I calculated by applying the recovery of spring-applied N to the whole of I, S and F is 45·6 kg (Table 7).

Values of I calculated in this way, using data from the spring and autumn ^{15}N experiments on Broadbalk, are overestimates, because those portions of I and S released in early autumn will almost certainly be used more efficiently than the labelled KNO_3, which was added after the wheat had emerged and which was greatly in excess of the needs of overwintering wheat. The real inputs of non-fertilizer N will almost certainly be somewhat greater than those given in Table 7, but are unlikely to be as large as those calculated using data from the experiment with autumn-applied N.

Jenkinson (1977) drew up a nitrogen balance for Broadbalk for the period 1852–1967. There was a non-fertilizer input of 41 kg N/ha per year to plot 5 (N_0), very similar to the calculated inputs to plot 5 in 1980 and 1981 (Table 7). However, the salient feature of Table 7 is that there is a substantial input of N from non-fertilizer sources to all plots, including those given N fertilizer.

In making the calculations, the soil N in plots 5, 6, 7 and 8 (N_0, N_1, N_2 and N_3) is taken as being under steady-state conditions. The total quantity of N in the 0–23 cm layer of these plots when sampled in 1980 (Appendix Table 1) is within 5% of that in the same plots when sampled 99 years earlier, in 1881, or in 1914, 66 years before (Jenkinson, 1977). Since 1968, yields of wheat and offtakes of N have increased considerably because of changes in crop variety and improved pathogen control (Table 6; see Dyke *et al.* 1983 and Jenkinson, 1982 for further details) and losses of nitrogen are now smaller than in the pre-1968 period. It is possible that S, the annual input of N to soil organic N, is greater than in the pre-1968 period because the larger crops grown in recent years return more roots, stubble and chaff to the soil. However, this extra return, if real, has not yet had a measurable effect on total N in topsoil. If it is real, then the annual input of non-fertilizer N will be even greater than that calculated in Table 7.

Part of the non-fertilizer input is readily accounted for by N in seed (4 kg/ha per year) and rain (about 10 kg/ha per year; Barrett, 1983; Brimblecombe & Pitman, 1980). This leaves an unexplained annual input of N in the range 15–45 kg/ha, or possibly more. The most likely source of this N is biological fixation of atmospheric N_2, although dry deposition of combined N may also contribute. Witty *et al.* (1979) demonstrated that biological fixation of atmospheric N_2 by blue-green algae on the soil surface does occur on Broadbalk and suggested that about 25 kg N/ha per year could be fixed by the plot not given N fertilizer.

Dry deposition of ammonia on crop and soil undoubtedly contributes to the non-fertilizer input of N measured on Broadbalk, but its magnitude is in doubt. Rodgers (1978) found that the annual deposition rate of ammonia (gaseous plus particulate) onto soil at Rothamsted was only 4 kg N/ha, with a mean atmospheric concentration of 2·1 g NH_3-N/m^3 (range 0·5–4).

The quantity of ammonium compounds in the atmosphere as particulate aerosols can often exceed the quantity of gaseous ammonia (Farquhar, Wetselaar & Weir, 1983). Dry deposition of such particles onto plants may make a significant contribution to N input, in addition to deposition onto soil; values of between 2 and 6 kg N/ha per year have been suggested (Farquhar *et al.* 1983; Tjepkema, Cartica & Hemond, 1981).

Nitric oxide and nitrogen dioxide can be absorbed by plants and soils (Galbally & Roy, 1983) and it has been suggested (Fowler, 1978) that dry deposition of NO_2 in suburban areas could be as high as 14 kg N/ha per year. However, concentrations of NO_x have increased markedly in recent decades, and the relatively constant offtake of N in the crop from plot 5 over the last 140 years (Jenkinson, 1982) makes it unlikely that any input process such as this which has changed markedly over a few decades could be a major contributor.

CONCLUSIONS

The findings of this paper are brought together in a diagram (Fig. 4), which shows the flow of N through the Broadbalk plot that has received 144 kg fertilizer N every year for nearly 150 years. It should be noted that this is the present flow: the

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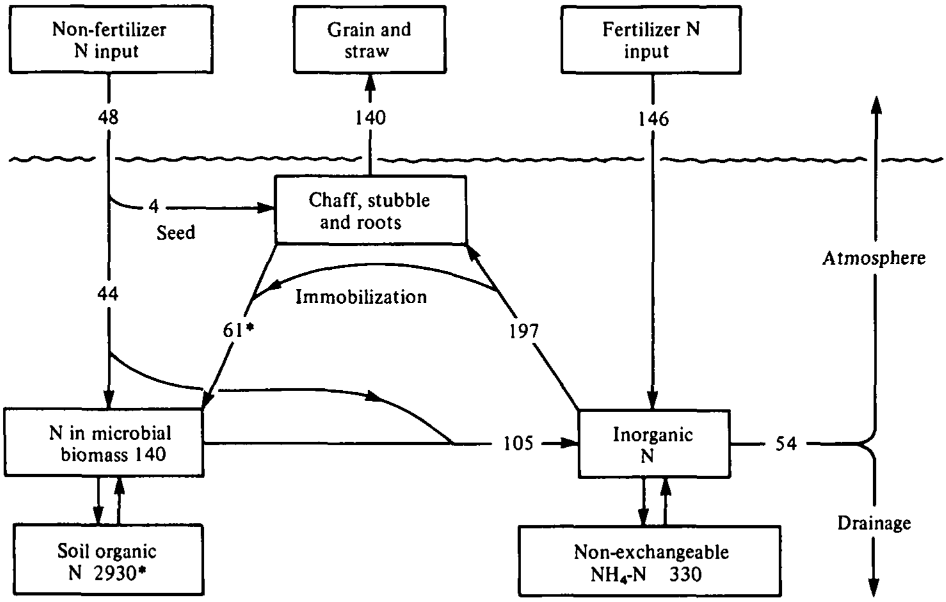

Fig. 4. N cycle under continuous winter wheat receiving (nominally) 144 kg N/ha every year (Broadbalk plot 8). Figures are means for the 4 years April 1980–April 1984, except those marked with an asterisk, which are means for the first 3 years and thus exclude measurements made on microplots within plot 9 which normally receives 192 kg N/ha. All N transformations are assumed to take place in the plough layer (0–23 cm). Microbial biomass N and non-exchangeable NH_4^+ measurements made by S. M. Shen (personal communication). Figures within boxes are kg N/ha; others are kg N/ha per year.

varieties of wheat grown in earlier times used N much less efficiently (Jenkinson, 1982).

The values in Fig. 4 for fertilizer and non-fertilizer inputs, crop offtake and loss are 4 year means of F, I, H and L respectively (Table 7). The quantity of N entering the pool of soil organic N (the mean value of S for the first 3 years, calculated from equation (3)) is 61 kg N/ha. This comprises the N present in the chaff, stubble and roots, plus that immobilized during their decomposition. Because soil organic N is under steady-state conditions, an equal quantity is mineralized each year. Despite the substantial quantity of fertilizer added every year, there is also a non-fertilizer input of 48 kg N/ha. Some of this input enters the inorganic N pool directly, as ammonium and nitrate in rain, or as particulate or gaseous ammonia deposition on soil, but some, for example biologically fixed N, will first enter the organic N pool and later be mineralized. In Fig. 4 it is assumed that all of the non-fertilizer input enters the soil, but this may not be so. If an amount Q kg N/ha is absorbed by the crop directly from the atmosphere, the non-fertilizer N entering the soil will be (48–Q) kg/ha and the quantity of N cycled through the soil will be correspondingly less.

Figure 4 shows that, of the total input of fertilizer and non-fertilizer N, 72% is harvested annually and 28% is lost from the crop–soil system.

The processes responsible for those inputs and losses of N that can be detected in the Broadbalk experiment are presumably operating in many other situations, both agricultural and natural, throughout the world. Further work is required to understand the processes involved in different environments, particularly where inputs of N fertilizer are low. In all environments, both agricultural and natural, a knowledge of these processes is necessary to an understanding of the overall nitrogen cycle.

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Appendix Table 1. *Dry weight of crop and weeds, labelled (L) and unlabelled (U) nitrogen content of crop and total nitrogen content of soil*

Year and N application rate	Dry weight of crop and weeds (t/ha)						N in crop (%)				Total N in soil (kg N/ha)		
	Grain	Chaff	Straw	Stubble	Total in crop	Weeds*	Grain	Chaff	Straw	Stubble	0–23 cm	23–50 cm	50–70 cm
1980													
N_0	1·23	0·37	1·17	0·40	3·16	ND	1·79	0·51	0·38	0·46	2875	—	—
N_1	2·72	0·65	2·09	0·66	6·12	ND	1·84	0·52	0·35	0·47	3114	—	—
N_2	4·77	1·00	3·63	0·85	10·26	—	2·02	0·56	0·41	0·53	3420	—	—
N_3	5·57	1·11	4·39	0·75	11·82	—	2·41	0·63	0·53	0·83	3590	—	—
N_4	6·22	1·23	4·87	1·02	13·34	—	2·41	0·69	0·61	0·88	3261	—	—
N_2 (no P, K or Mg)	3·06	0·74	2·47	0·56	6·82	ND	2·40	0·60	0·49	0·58	3092	—	—
S.E.†	0·157	0·030	0·171	0·110	0·329		0·017	0·031	0·010	0·043	102		
1981													
N_0	1·23	0·37	1·47	0·45	3·51	1·03	1·75	0·53	0·35	0·50	2931	—	—
N_1	3·60	0·91	3·50	0·83	8·83	0·48	1·61	0·55	0·27	0·45	3065	2954	1514
N_2	5·55	1·31	5·07	0·77	12·70	—	1·79	0·76	0·35	0·69	3321	—	—
N_3	5·38	1·24	5·08	1·01	12·72	—	1·99	0·99	0·49	0·79	3341	—	—
N_4	5·48	1·35	5·36	1·08	13·28	—	2·23	1·21	0·69	0·81	3291	2715	1784
N_2 (no P, K or Mg)	3·21	0·88	2·60	0·67	7·36	0·59	2·06	0·72	0·36	0·56	3067	—	—
S.E.†	0·208	0·036	0·181	0·109	0·401		0·036	0·030	0·024	0·062	67	88	140
1982													
N_0	0·76	0·49‡	0·88	0·21	2·34	1·08	1·86	1·00	0·32	0·54	—	—	—
N_3	4·37	1·90‡	3·87	0·77	10·92	—	2·28	1·29	0·50	0·75	3266	2779	1760
1983													
N_0	1·30	0·37	1·20	0·34	3·21	0·82	1·75	0·46	0·27	0·42	—	—	—
N_3§	5·01	1·17	5·64	0·61	12·43	—	2·18	0·51	0·43	0·67	2938	2887	—
N_0‖	2·25	0·53	2·32	0·42	5·53	—	1·79	0·48	0·30	0·49	—	—	—

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Year and N application rate	Labelled (L) and unlabelled (U) N in crop and weeds (kg N/ha)									
	Grain		Chaff		Straw		Stubble		Weeds	
	L	U	L	U	L	U	L	U	L	U
1980										
N_0	0	21·9	0	1·9	0	4·5	0	1·8	0	ND
N_1	19·7	30·4	1·3	2·1	2·1	5·1	0·8	2·3	ND	ND
N_2	48·6	47·7	3·2	2·5	6·9	7·8	1·6	3·0	—	—
N_3	77·9	56·2	3·9	3·0	12·0	11·5	2·5	3·6	—	—
N_4	96·7	53·0	5·1	3·3	15·5	14·4	4·0	4·9	—	—
N_2 (no P, K or Mg)	33·0	40·3	1·7	2·7	4·6	7·4	1·0	2·3	ND	ND
S.E.†	2·17	1·61	0·27	0·28	0·62	0·54	0·24	0·47		
1981										
N_0	0	21·6	0	1·9	0	5·1	0	2·3	0	12·4
N_1	19·5	38·4	1·7	3·2	3·4	5·9	1·0	2·5	0·1	6·4
N_2	44·5	54·9	4·6	5·3	8·5	9·1	1·9	3·4	—	—
N_3	55·2	51·7	6·6	5·8	13·5	11·3	3·3	4·4	—	—
N_4	74·6	47·4	10·4	6·0	22·8	14·0	4·2	4·4	—	—
N_2 (no P, K or Mg)	29·6	34·0	3·0	3·3	4·3	5·0	1·4	2·9	0·3	9·0
S.E.†	1·99	3·57	0·25	0·38	0·59	0·62	0·23	0·33		
1982										
N_0	0	14·2	0	4·9	0	2·8	0	1·1	0	14·2
N_3	64·5	34·5	16·4	8·3	12·5	6·8	3·0	2·8	—	—
1983										
N_0	0	22·8	0	1·7	0	3·2	0	1·4	0	9·4
N_3§	65·8	43·2	3·6	2·3	15·4	8·8	2·2	1·8	—	—
N_0‖	1·7	38·4	0·1	2·6	0·3	6·7	0·1	2·0	—	—

* Weeds negligible in plots 7 (N_2), 8 (N_3) and 9 (N_4).
‡ Incomplete separation of grain from chaff: see Table 4.
‖ Discard area of plot 8 given N_3 (labelled) in 1982 but no N fertilizer in 1983.
† Standard error of means.
§ Discard area of plot 9 (N_4) given N_3 in 1983 only.
ND, Not determined.

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