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The nitrogen cycle in long-term field experiments

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Nitrogen balance sheets for the Rothamsted Continuous Wheat Experiment show that N fertilizers were used very inefficiently in the past. Thus, over the period 1852–1967, the apparent recovery (in grain and straw) of the fertilizer N applied to the plot receiving 144 kg N ha^{-1} each year was 32%. Recently, however, the apparent recovery of fertilizer N has increased and for the two years 1979 and 1980 the mean value in this plot was 86%. Increased recovery is mainly due to new, high-yielding varieties of winter wheat that take up more fertilizer N, to better control of pests and diseases and to earlier sowing in autumn. Early sowing can increase the amount of N overwintering inside the plant instead of outside in the soil, where it is subject to losses through leaching and denitrification. Recoveries of N by spring-sown barley on the Rothamsted Continuous Barley Experiment were lower than with winter wheat, as would be expected under a cropping system in which the soil is without plant cover from August until March or April.

Tentative national N balance sheets for the two major cereal crops in the U.K., wheat and barley, are set out, based on crop survey data. In these balance sheets, between one-third and one-half of the chemically combined N reaching the soil is not recovered in grain and straw. Recoveries of N on the Rothamsted Classical Experiments show that there is considerable scope for improving the recovery of N on a national scale. Research into the quantitative aspects of the nitrogen cycle in the field is needed in order to understand how this N is lost and how the losses can be diminished.

Introduction

Long-term experiments are useful in studying the nitrogen cycle, in that slow changes can be observed and followed. They can also be used to see if a particular soil–plant system is at or close to equilibrium. If this can be established, annual changes can then be examined on a 'steady-state' basis, with annual inputs and outputs in balance.

The Rothamsted long-term cereal experiments

These experiments, on cereal monoculture, were laid down towards the middle of the last century. Figure 1 shows the N content of soil from three plots of the best known of these experiments, the Broadbalk Continuous Wheat Experiment, described in detail by Johnston & Garner (1969). In two of these plots, that receiving P, K and Mg fertilizers, and that receiving N, P, K and Mg fertilizers, there has been little change in the total N content of the soil over the last 100 years. Steady-state conditions can therefore be assumed to hold for these two plots, at least up to 1967.

Table 1 presents a N balance sheet for two plots on Broadbalk, covering the period 1852–1967, excluding the first few years of the experiment, when the manurial treatments had not yet settled into the pattern that remained relatively unchanged until 1968. The salient feature of

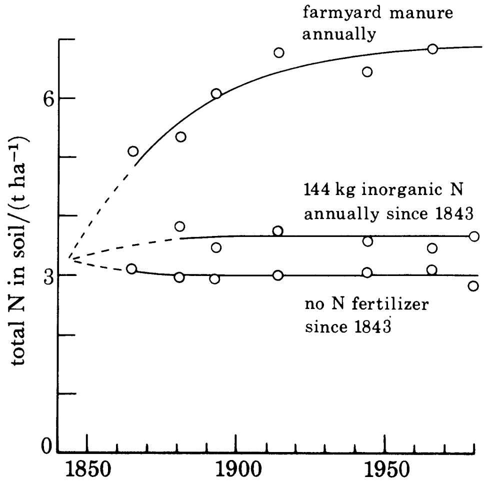

FIGURE 1. Total N in soil (0–23 cm) from three plots on the Broadbalk Continuous Wheat Experiment; the plot (22) receiving 35 t ha^{-1} farmyard manure annually, the plot (08) receiving complete inorganic fertilizer annually (144 kg N ha^{-1}, 35 kg P ha^{-1}, 90 kg K ha^{-1} and 10 kg Mg ha^{-1}), and the plot (05) receiving non-nitrogenous inorganic fertilizer annually (35 kg P ha^{-1}, 90 kg K ha^{-1} and 10 kg Mg ha^{-1}).

TABLE 1. NITROGEN BALANCE (KILOGRAMS N PER HECTARE PER YEAR) ON TWO PLOTS OF THE BROADBALK CONTINUOUS WHEAT EXPERIMENT, 1852–1967

(From Jenkinson (1977).)

	PKMg (plot 05)	NPKMg (plot 08)
input		
from soil organic nitrogen	0	0
from rain	5	5
from seed	3	3
from fertilizer	0	144
output		
removed in grain and straw	27	73
to drainage	14	48
net annual gain from (+) or loss to (−) the atmosphere	+33	−31

table 1 is that the plot receiving no N fixed about 30 kg N ha^{-1} annually from the atmosphere. This has been sufficient to grow a small crop of wheat year after year, without depleting the organic N reserves of the soil. The plot receiving 144 kg fertilizer N each year lost about 50 kg N ha^{-1} per year in the drainage as nitrate; another 30 kg was unaccounted for, presumably being lost by denitrification, volatilization of ammonia or other processes. The overall apparent recovery of fertilizer N in grain and straw, defined as

$$100\,\frac{(\text{N uptake by fertilized crop})-(\text{N uptake by unfertilized crop})}{\text{fertilizer N application}},$$

was only 32 %.

In 1968 the Broadbalk experiment was modified to bring it nearer to modern agricultural practice, although the main fertilizer application rates remained unchanged. Largely as a result of the introduction of modern varieties of wheat, earlier sowing and improved methods for the control of pests and diseases, yields have greatly increased on the plots receiving N fertilizer (figure 2) and are now well above the national average, although not as large as on the best modern experiments at Rothamsted.

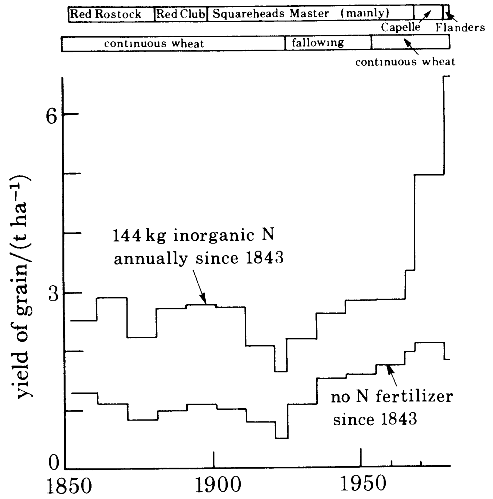

FIGURE 2. Yield of grain (85% dry matter) on two plots of the Broadbalk Continuous Wheat Experiment. The NPKMg plot (08) receives 144 kg N ha^{-1}, 35 kg P ha^{-1}, 90 kg K ha^{-1} and 10 kg Mg ha^{-1} annually; the PKMg plot (05) the same but omitting N.

TABLE 2. UPTAKE OF N BY CROP IN GRAIN AND STRAW

(A. E. Johnston, personal communication.)

N fertilizer	winter wheat†		spring barley‡	
kg ha^{-1}	uptake kg ha^{-1}	recovery of fertilizer N (%)	uptake kg ha^{-1}	recovery of fertilizer N (%)
0	22.3	—	22.9	—
48	57.3	73	45.9	48
96	110.2	92	78.8	58
144	145.4	86	95.7	51

† Broadbalk Continuous Wheat Experiment, mean of results for 1979 and 1980 (variety Flanders).
‡ Hoosfield Continuous Barley Experiment, mean of results for 1979 (variety Julia) and 1980 (variety Georgie).

Table 2 shows the mean uptakes of N in 1979 and 1980 on four plots of the Broadbalk Continuous Wheat Experiment, and also on four equivalent plots on the Hoosfield Continuous Barley Experiment. Recoveries of fertilizer N (now applied as a single dressing of Nitro-Chalk in mid-April) by winter wheat are much greater than in the past. Thus, of the 144 kg N ha^{-1} application, 86% was recovered in grain and straw, compared with 32% during the period 1852–1967. As with yield, this improvement is in part due to improved varieties of wheat, partly to earlier sowing and partly to better control of pests and diseases. Compared with the old varieties, modern wheats give more dry matter, containing an increased percentage of N, from a given application of fertilizer N. This increase in N content is mainly due to the increased grain:straw ratio in the modern short-strawed varieties of wheat, the N content of grain being some four or five times that of the straw. In the past, the N application (as ammonium sulphate) was split, 25 kg of fertilizer N being applied in the autumn and the rest in spring. Autumn-applied N is more subject to loss than N applied in spring, and this too will have depressed percentage recoveries in the period 1852–1967.

N recoveries are lower with barley than with winter wheat, even today with improved varieties and techniques. Thus the apparent recovery of fertilizer N by spring-sown barley in a plot receiving 144 kg N ha^{-1} was 51 %, the corresponding recovery by winter wheat being 86 % (table 2).

Table 3. Effect of sowing date on the uptake of soil N (kilograms per hectare) by wheat during the winter 1979/80

sampling date	early sown (20 September) in wheat†	early sown (20 September) in soil‡	late sown (19 October) in wheat†	late sown (19 October) in soil‡
December§	30	—	3	—
March§	55	5	11	60

† Penny & Widdowson (1981); data from Rothamsted Factors Limiting Yield Experiment.
‡ Widdowson & Penny (1981); values are for NO_3^--N to a depth of 90 cm. Initial NO_3^--N content 78 kg ha^{-1} (20 September).
§ Fertilizer N not applied until *after* the March sample had been taken.

Table 4. Uptake of N (kilograms per hectare) from fertilizer and from soil by winter wheat growing on Broadbalk in 1980

(From Jenkinson *et al.* (1981).)

	from soil	from fertilizer†
in grain	55.3	76.7
in chaff	2.9	3.8
in straw	11.2	11.7
in stubble and crowns	3.4	2.4
labelled N in soil (0–23 cm) at harvest		24.6
^{15}N recovered in crop and soil		84.5 %

† Uniformly labelled $^{15}NH_4{}^{15}NO_3$, applied at 141 kg N ha^{-1}.

A most important reason for the very high recoveries now being observed with winter wheat is the trend towards earlier sowing. By spring, an early-sown crop contains much more N than a late-sown one. Table 3 shows that, by spring, a September-sown winter wheat crop contained five times more N than a crop sown a month later. N overwintering in the crop is not subject to losses by leaching or denitrification, as is NO_3^--N overwintering in the soil.

Nitrogen cycle in the Broadbalk Continuous Wheat Experiment

Last year an experiment with ^{15}N labelled fertilizers was laid down on Broadbalk. The experiment is designed to last several years and we hope that it will enable us to draw up detailed N balance sheets for winter wheat, although this is not the main aim of the work, which is to measure the N-supplying capacity of the soil, as distinct from that of added fertilizer N.

Some results from the first year of the experiment are shown in table 4. Recoveries of ^{15}N in 1980 were high, some 80–85 % of the fertilizer N being found in the grain, chaff, stubble and soil (sampled to a depth of 23 cm). Had the soil been sampled deeper, recoveries would doubtless have been even higher.

Figure 3 shows a nitrogen cycle diagram for winter wheat receiving 144 kg N ha^{-1} on Broadbalk, from data in tables 2 and 4. The soil is assumed to be under steady-state conditions: whether or not this is true during a period of rapidly changing yields (figure 2) is under

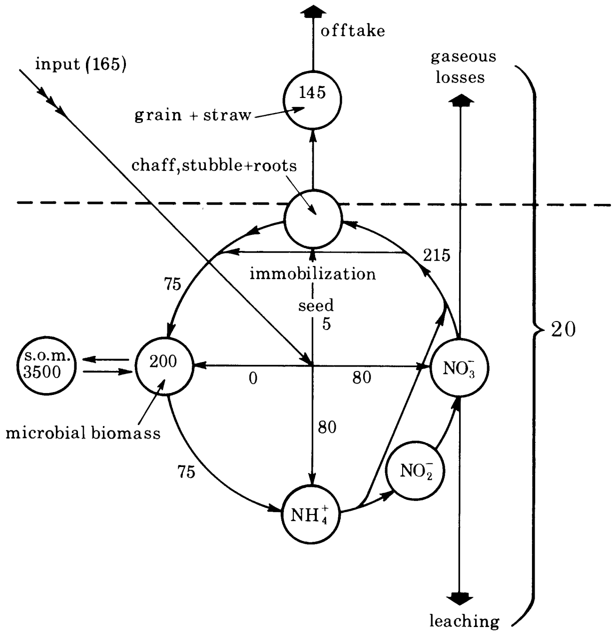

FIGURE 3. Nitrogen cycle under continuous winter wheat receiving NPKMg fertilizer annually (Broadbalk plot 08, section 1). All figures are rounded (usually to the nearest 5 kg) to avoid any spurious appearance of precision.

input/(kg N ha^{-1})		output/(kg N ha^{-1})	
seed	5	grain	130
rain and dry fixation	15	straw	15
biological fixation	0	unaccounted for	20
fertilizer	145		**165**
	165		

investigation. The quantity of N returned to the soil (0–23 cm) each year (in roots, root exudates, stubble and chaff) is calculated from the amount of ^{15}N-labelled fertilizer N remaining in the soil at harvest (table 4), assuming that the atom percentage excess of ^{15}N in the stubble and crowns (which were analysed) was the same as in the roots and exudates (which were not). Biological N_2 fixation has been assumed to be zero, an assumption unlikely to be far wrong in a plot receiving 144 kg N ha^{-1}. Losses to the atmosphere and to drainage were not measured, merely representing the quantity of N needed to balance the system, and so harbour all the errors in the various measurements, estimates and guesses. A striking feature of the diagram is the very considerable quantity of N supplied to the crop annually by the soil: 75 kg ha^{-1}.

TABLE 5. BARLEY AND WHEAT PRODUCTION IN ENGLAND AND WALES

	wheat†		barley‡		
	1979	1980	1979	1980	
				spring	winter
area§/Mha	1.35	1.41	1.86	1.11	0.72
average yield§/(t ha^{-1}) (85% dry matter)	5.22	5.70	4.06	4.36	5.28
overall average fertilizer application‖/(kg N ha^{-1})	133	144	96	87	129
area receiving farmyard and other organic manures‖/Mha	0.18	0.18	0.33	0.24	0.08
mean percentage N in *dry* grain (U.K.)¶	2.00	2.12	1.71	1.90	2.02

† Of which spring wheat made up 2% in 1979, 3% in 1980.
‡ Of which spring barley made up 30% in 1979.
§ Ministry of Agriculture, Fisheries and Food, *Annual agricultural statistics*.
‖ Church (1980, 1981).
¶ Home Grown Cereals Authority (1980, 1981).

TABLE 6. NITROGEN BALANCE (KILOTONNES) FOR THE TWO MAJOR CEREAL CROPS IN ENGLAND AND WALES

	wheat		barley		
	1979	1980	1979	1980	
				spring	winter
input					
from fertilizers†	180	203	179	97	93
from farmyard manure and other organic fertilizers‡	27	27	50	36	12
from seed, rain and dry deposition§	27	28	37	22	14
output					
in grain†	120	145	110	78	65
in straw‖	11	19	18	17	14
losses					
to atmosphere and drainage ¶	103	94	138	60	40

† From data in table 5.
‡ Taken as 150 kg N ha^{-1}, i.e. an application of 15 tons per acre, containing 0.4% N.
§ Taken as 20 kg N ha^{-1}.
‖ Calculated from the grain-N:straw-N ratios (11.0 and 7.8 respectively for the 1979 and 1980 Broadbalk wheat data in table 2; 6.1 and 4.7 for the 1979 and 1980 Hoosfield barley data, also in table 2).
¶ Assuming the soil is under steady-state conditions.

NATIONAL N BALANCE SHEETS

Regional and national N balances are particularly difficult to draw up in the United Kingdom, with its complex patterns of soil, land use and agriculture. Cereal nitrogen cycles are relatively simple, compared with, say, nitrogen cycles under grazed grassland, with rapid recycling of N through the animal. Yet even with cereals it is not yet possible to set out a N balance on a national or regional basis in anything but the crudest form. Some of the problems involved are illustrated by the data in tables 5 and 6. Table 5 gives the areas in England and

Wales under the two major cereal crops wheat and barley in 1979 and 1980, together with the national mean yields, average fertilizer N applications and the N contents of the produce. Table 6 gives N balance sheets for wheat and barley in each of the two years, as calculated from the data in table 5. Taken at their face value, the figures show that from one-third to one-half of the N added from fertilizers, both organic and inorganic, from the atmosphere and from seed is lost. Losses of N were larger in 1979 than in 1980, in accord with the data from the Rothamsted Classical Experiments. Losses were greater from barley (mostly spring) than from wheat (almost entirely winter-sown) in 1979, but in 1980, with better all-round recoveries of N, differences between the two crops were smaller.

FIGURE 4. Areas under tillage, under wheat and under wheat and barley combined, in England and Wales, 1866–1979 (Ministry of Agriculture, Fisheries and Food (1968), and subsequent issues of *Annual agricultural statistics*).

It is instructive to set out the assumptions behind the calculations in table 6. The nitrogen cycle is taken to be in balance, with annual input balanced by annual output. This is almost certainly not true of England and Wales as a whole. Figure 4 shows how the area of arable land has varied over the last century. This change in land use will be reflected, in a sluggish way, by changes in the organic N content of the soil (figure 1). It is likely that the old grasslands ploughed up during and since World War II still mineralize more N each year than they immobilize. Again steady-state conditions imply that the cereals are not the N-depleting crop in a rotation containing a N-accumulating crop, for example the wheat that followed clover in the old Norfolk four-course rotation. If cereals form part of a rotation, the steady-state assumption is best applied to the rotation as a whole, not just one part of it. Quite apart from the validity of the steady-state assumption, many of the data in table 5 are based on sample surveys and may contain substantial biases. The values in table 6 for N from organic manures are particularly questionable, being based on the supposition that all fields receiving organic manures receive the same amount: 150 kg N ha^{-1} per year. Biological N_2 fixation is assumed to be negligible, an assumption unlikely to be far wrong for heavily fertilized cereals.

National N balances such as that in table 6 are of trivial scientific interest, and would still be so even if the surveys on which they are based were accurate. They do not partition losses into those to the atmosphere and those to drainage, they do not show the annual flux of N into and out of soil organic matter, and they do not show how much N is fixed biologically.

Future work on the nitrogen cycle

There is considerable scope for increasing the efficiency of use of fertilizer N: farmers in the U.K. spend roughly £400M on N fertilizers each year, and a substantial part of this is wasted (table 6). Some leaks in the nitrogen cycle are unavoidable and there is unlikely to be any simple cure for those that are not. Accurate matching of fertilizer application to crop need will help, as will correct timing of fertilizer applications, particularly if this can be linked to reliable long-term weather forecasts. The benefits are that expensive N is not wasted and that the quantity of N entering drainage water can be minimized. Policies aimed at keeping the area of land overwintering without plant cover as small as economically and agronomically possible will also help, as will the early establishment of autumn-sown crops. Nitrification inhibitors may prove useful in certain situations, although it is difficult to see how they will make much impact on British agriculture, where N is mainly applied in spring, and where the battle against nitrification is already half lost, most fertilizer N being applied as ammonium nitrate.

One area where considerable progress has recently been made is in assessing the quantity of inorganic N that has successfully overwintered in the soil and is still accessible to plant roots. Mathematical models are now available for predicting this, based on a knowledge of soil type and the quantity and distribution of winter rainfall (Burns 1980; Addiscott 1980). This work will help to understand year-to-year variations in N uptake by crops, although of course the amount of nitrate present in the root zone in spring is only one factor involved.

The N in organic manures can doubtless be recycled and used more efficiently. Organic manures are, however, basically less flexible than inorganic fertilizers in their use: they are expensive to transport and part of the N present in the original animal excreta is commonly lost before application to the land. Again, organic manures are produced at times of the year when they are not needed and must be stored, usually with loss of N.

There is also need for work on the more basic side of the nitrogen cycle in the soil–plant system. We need to know how much N is incorporated into soil organic matter each year and how much N is released, if accurate predictions of the N-supplying capacity of the soil are to be made. Experiments with ^{15}N (for example those described in table 4) have already shown how large these quantities of N are; we need to know how they are affected by cropping history, crop, soil and season. We also need information on gaseous losses to and gains from the atmosphere, whether these gains be biological or chemical, whether the losses be from the soil, the manures or the plant, whether they be as NH_3, N_2O, NO_2, N_2, or in other forms. Although we know, for example, the conditions under which nitrate is lost by denitrification, we do not know how much is lost.

We need to concentrate on the *quantitative* study of the nitrogen cycle in the field: if this is done properly, the data needed for the construction of accurate regional and national N balances will emerge as a useful by-product.

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