Agricultural Productivity and the Nitrogen Cycle [and Discussion]

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Agricultural productivity and the nitrogen cycle

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During the past 30 years agricultural production in the U.K. has consistently increased as the result of a number of technological changes. For example, cereal yields have doubled and milk yields from dairy cows have increased by one and a half times. Livestock numbers have also increased, particularly those of pigs and poultry. The use of fertilizer nitrogen has increased fivefold in the same period. This greater productivity means that not only have the inputs of nitrogen to agriculture increased but so also have the amounts circulating within agricultural systems. These changes are examined and the implications of their effects on the environment assessed.

Introduction

'He gave it for his opinion; that whoever could make two ears of corn, or two blades of grass to grow upon a spot of ground where only one grew before; would deserve better of mankind and do more essential service to his country than the whole race of politicians put together'. (Jonathan Swift (1667–1745): *Gulliver's travels; voyage to Brobdingnag*, chapter 7).

This quotation, used by the Royal Commission on Environmental Pollution at the start of its Seventh Report, emphasizes two points relevant to agriculture and the nitrogen cycle. First, agriculture is concerned with the production of food, whether as crops for direct consumption or as animal products. Secondly, farming affects the environment and may therefore attract the attention of politicians and legislators, particularly if the effects are considered to be contrary to the good of the public.

As an industry, agriculture needs to continue increasing its productivity if it is to remain economically viable. In the U.K. with a slowly decreasing area of land available for agriculture, this requires increased output per unit of land, a result that has been achieved over the past 30 years by a smaller worker force with more mechanization. The steadily increased output is illustrated in figure 1 for yields of wheat and milk. These increased yields are the result of several factors such as improved crop varieties, more productive livestock, better weed and pest control and the increased use of fertilizer N. Figure 2 shows the amounts of N, P and K fertilizers used annually from 1960 to 1980. In 1960 the use of all three fertilizers increased to more than 400 kt, and the use of N has increased almost linearly for the last 20 years to more than 1.2 Mt, whereas consumption of P and K has changed little.

Agriculture differs from natural ecosystems because, in farming, controlled operations are aimed at improving the conversion of solar and fossil energy into food. However, farming is still both an art and a science because of the difficulty of measuring and predicting the effects of some variables, such as soil physical conditions, to allow exact control of farming operations and the large number of uncontrolled variables particularly the weather. The lack of precision in forecasting makes day-to-day planning uncertain because weather exercises a great influence on crop production and particularly affects the demand for and utilization of N by crops.

Agriculture and water supplies

Much of the land used for agriculture is also used as catchments for water supplies, whether by surface abstraction or for the recharging of groundwaters. Farming affects the composition of the water leaving the soil and therefore its quality. Some effects, such as the increase in calcium content from liming, do not create problems; other effects, particularly increases in the phosphorus and nitrate contents of water, are considered undesirable because increased contents lead to increased biological activity, especially the growth of algae, which can create environmental problems and difficulties for the water supply industry. Large concentrations of nitrate in drinking water are to be avoided because they may create health hazards. The World Health Organization (W.H.O.) recommended that water for drinking should contain less than 11.3 mg NO_3-N l^{-1}, although up to twice this concentration is acceptable. When nitrate reaches these concentrations the process is usually called pollution, and some agricultural operations can pollute water, even though they may be good farming practice.

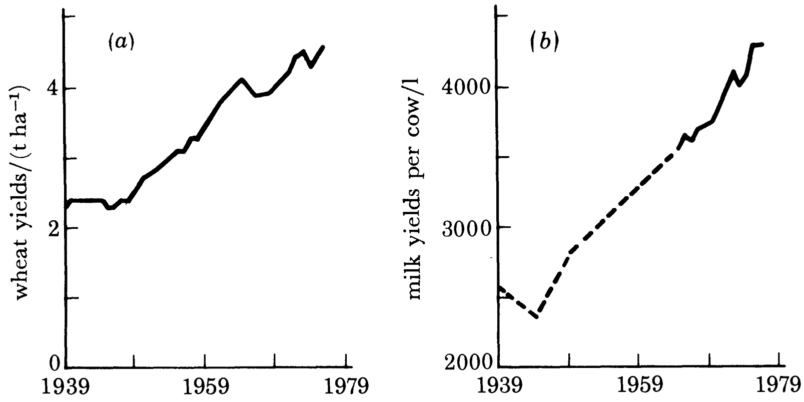

FIGURE 1. Yields of wheat and milk from 1939 to 1979. Sources of data: (*a*) M.A.F.F., for Great Britain; (*b*) Milk Marketing Board *Dairy facts and figures*, for England and Wales. (Reproduced with permission of the Controller of Her Majesty's Stationery Office and the Milk Marketing Board.) (R.C.E.P. (1979).)

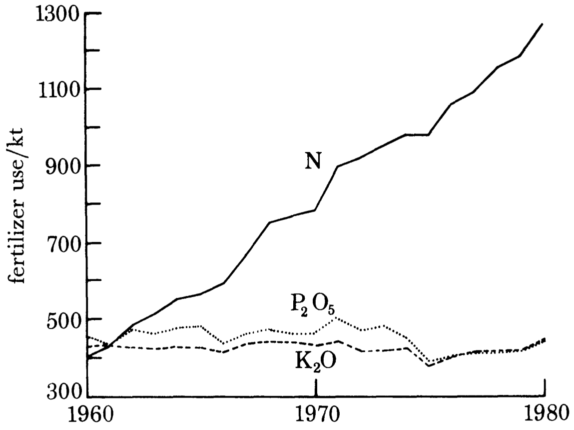

FIGURE 2. Fertilizer consumption 1960–1980. (Source: fertilizer statistics, Fertilizer Manufacturers Association.)

Gaseous N *products from the soil and animal effluents*

Soils emit both oxidized and reduced gaseous N products. The main losses from soil are as ammonia under alkaline conditions, and as nitrous oxide and N_2. Ammonia and nitrous oxide take part in reactions in the atmosphere. Ammonia will be lost from ammonium salts applied to calcareous soils and from urine and faeces from grazing animals after decomposition. Ammonia is also lost from animal effluents from housed animals both during storage and after spreading. Under reducing conditions, nitrate present in the soil or in manures or applied as fertilizer may be denitrified to form nitrous oxide and N_2. Nitrous oxide is also formed during the nitrification of ammonium.

Table 1. Fertilizer used (from fertilizer statistics, Fertiliser Manufacturers Association) in the U.K. and energy required for its production

	fertilizer used/kt			energy required/PJ †		
	1959–60	1969–70	1979–80	1959–60	1969–70	1979–80
nitrogen (N)	404	783	1268	31.1	60.3	97.6
phosphorus (P_2O_5)	455	463	440	6.5	6.6	6.3
potassium (K_2O)	426	431	444	3.5	3.6	13.7
total				**41.1**	**70.5**	**107.6**
N (percentage of total)				76	86	91

† PJ = petajoule = 10^{15} J.

Table 2. Primary energy consumed in U.K. agriculture, 1978 (White 1980)

	primary energy/PJ	percentage of total
solid fuel	1	0.3
petroleum	70	20.5
electricity	33	9.7
fertilizer	102	29.7
machinery	40	11.7
feedstuff processing (off-farm)	53	15.5
chemicals	9	2.6
buildings	14	4.1
transport, services	16	4.7
miscellaneous	4	1.2
total	**342**	**100.0**

NITROGEN FIXATION

Nitrogen may be fixed biologically or chemically; both processes require energy. For biological fixation, most N_2 is fixed symbiotically and the energy is provided by photosynthesis. For chemical fixation, almost all the energy is provided by fossil fuels. Table 1 gives the amounts of fertilizers used in 1960, 1970 and 1980 and the energy required for their production. These figures illustrate both the large amount of energy needed and the increasing proportion required for N compared with that for P and K. Fertilizers are the most energy-demanding input to agriculture in the U.K. and table 2 shows that in 1978 they required about 30% of the energy used by agriculture. The next largest energy use was as petroleum fuel, which included tractors and other machinery, glasshouse heating and crop drying. Therefore, for reasons both of economy and energy conservation, the best use should be made of fertilizer N. However, in the context of the total energy required to put food on the table, table 3 shows that less energy was needed for primary agricultural production than for packaging, transport and marketing, or for preparing and cooking food. In the national context, the energy needed to supply fertilizer N is about 1 % of total energy usage in the U.K. In contrast, agriculture produces enough energy as crops to meet the basic needs of the population of the U.K., but because of the demand for animal products with the lower conversion rates of primary energy to food (White 1976), it provides a smaller proportion of the food supply.

TABLE 3. PRIMARY ENERGY INVOLVED IN FOOD PRODUCTION IN THE U.K., 1973 (WHITE 1980)

	primary energy/PJ	percentage of national consumption
agriculture (to the farm gate)	361	3.9
processing, packaging distribution	648	7.0
food storage and preparation	449	4.9
total	**1458**	**15.8**

TABLE 4. AMOUNTS OF N RELEASED ANNUALLY FOR ARABLE CROPS AFTER VARIOUS CROPPING SYSTEMS (COOKE 1975)

preceding cropping	annual release of N / kg ha^{-1}
arable land	
continuous cereals	40
after potatoes	80
after beans	80
grassland and forages	
after old grass	100
after grazed ley	140
after lucerne	100

THE SUPPLY OF N IN AGRICULTURE

The main inputs of N to agriculture are the mineralization of the soil organic N, symbiotic fixation by rhizobia, and fertilizers. Considerable amounts of N are recycled directly as faeces and urine from grazing animals, and an almost equal amount as slurries and manures from housed animals. Spreading the latter may represent a transfer between different parts of the farming system. The amounts produced by the soil for arable crops, applied as fertilizer and present in animal effluents can be quantified; amounts fixed symbiotically, particularly in grassland, are much less certain.

In arable agriculture, preceding cropping will affect the amount of N released for current crops. Values in table 4 show that least will be formed after a cereal crop in continuous cereal growing and most after ploughing grassland or lucerne (Cooke 1975). No arable system provides enough N for the maximum production of crops, and the additional N must be added as organic manures or fertilizer to allow optimum crop production. Table 4 shows that in arable farming the previous cropping can alter the amount needed to be added by 100 kg N ha^{-1}, but at present we have no precise method for measuring the amount of mineral N that will be released for a crop and therefore for adjusting the amount added. However, the Survey of Fertiliser Practice (Church & Leech 1981) shows that, for all crops, farmers do apply various amounts of fertilizer N but the basis of their judgement is not known. The percentages of crop area receiving increasing amounts of fertilizer N are show in figure 3 for spring barley, main crop potatoes and 2-7 year leys. For spring barley and potatoes, the amount applied is largely contained within two or three classes being 50–125 kg N ha^{-1} for barley and 150–250 kg N ha^{-1} for potatoes. Experimental evidence suggests that arable crops are receiving close to optimum amounts of N, the small area of barley receiving up to 200 kg N ha^{-1} does not have more N than the crop can take up, and, because the total area of the potato crop is about 200 kha, that receiving more than 250 kg N ha^{-1} means that the amount of fertilizer at risk is very small.

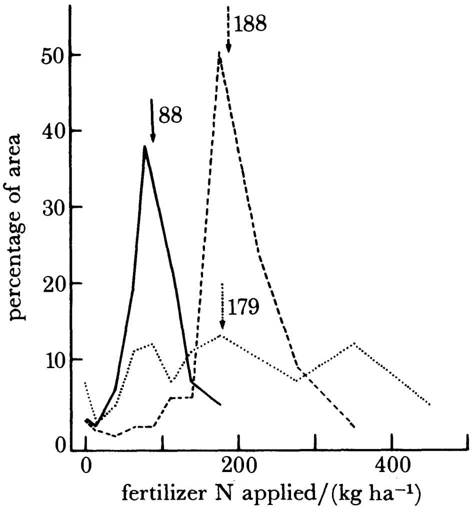

FIGURE 3. Percentages of crop area getting different amounts of fertilizer N. ——, Spring barley, – – – –, main-crop potatoes; ..., 2–7 year leys; ↓, actual average dressing applied (Church & Leech (1981).)

In marked contrast to arable crops, figure 2 shows that application to grassland 2–7 years old was nearly uniform across the range 50–400 kg N ha^{-1}, and for grassland the use of average dressings provides no information about the input to particular fields and the way the grass is utilized and therefore about possible effects on the nitrogen cycle and leakage from the system to water or the atmosphere.

Information given to the Royal Commission on Environmental Pollution (R.C.E.P. 1979) suggested that the amount of fertilizer N used will increase by about one-half by the year 2000 and most of the increase would be applied to grassland. This rate of increase is very similar to the trend for the past 20 years shown in figure 2. The effect of this extra N on the distribution of areas receiving various amounts of N is not known, nor are the effects on the nitrogen cycle and leakages from the agricultural system. Therefore, in considering changes in the average amounts of fertilizer N in the past and prospects for the future, consideration should also be given to the range of amounts applied.

The increasing use of fertilizer N results in larger crop residues from arable crops containing a greater percentage of N, which may be expected to release more mineral N on decomposition in the autumn; for grassland, there is more total N in circulation. Earlier work showed that not only do legumes increase the amount of available N when ploughed out for arable crops, but also increasing the amount of N applied to grass swards that were cut and herbage removed increased the mineralizable N when they were subsequently ploughed (Gasser 1968).

Changes in the forms of N and losses from animal effluents and fertilizer

Figure 4 shows schematically the decomposition of animal excreta and of urea to form ammonium and subsequent changes in inorganic N from these sources or added as fertilizer. This scheme identifies the possibilities for leakage and loss of nitrogen from the agricultural cycle at several points and illustrates that the application of N as organic materials, ammonium or nitrate all have advantages and disadvantages.

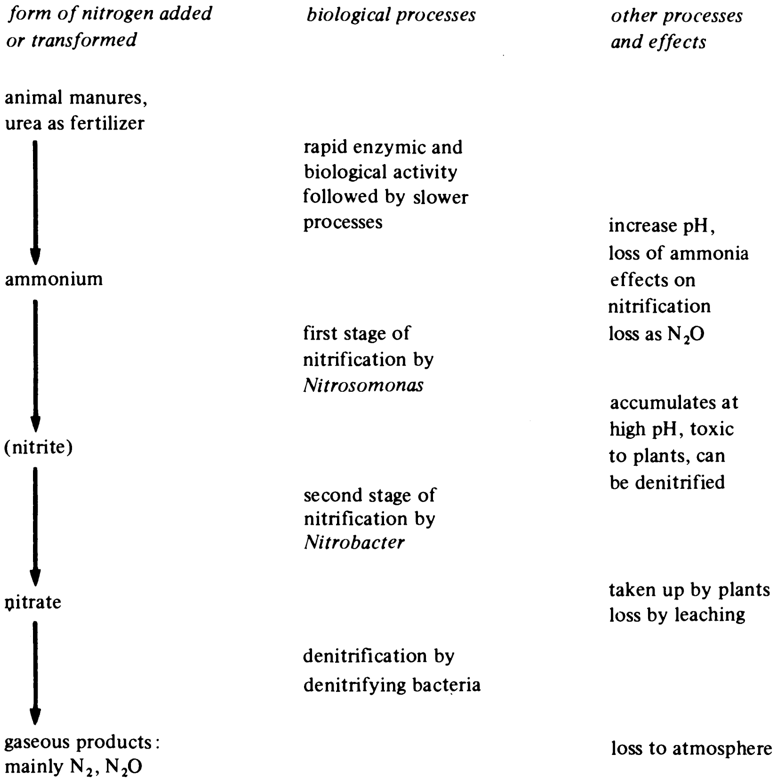

Figure 4. A model scheme for the transformations, movement and loss of nitrogen in agriculture.

Losses from slurry and urea

Slurry consists of faeces and urine together with varying amounts of other organic materials, such as bedding and spilt feed, and water. The amount of water added will vary from none or very little to several times the original volume of slurry depending on the conditions. In the field, faeces and urine are often voided separately and their N is almost entirely in organic forms, with a little ammonium. Oxidized forms are normally absent. Urea N predominates in the urine and more complex forms in faeces (Doak 1952; Petersen *et al.* 1956). However, the urea is decomposed rapidly with some of the other readily degraded organic compounds to yield ammonia, so that urea is effectively absent from slurry as handled. These processes, together with the following ones, are represented schematically in figure 4.

The ammonium carbonate formed on the decomposition of urea increases the pH of the slurry and the soil, and there is usually some loss of N as ammonia. The losses of ammonia from slurries applied to soils have not been measured, but useful analogies may be drawn from the loss of ammonia from urea applied to soils, which has been extensively studied. Two important factors were found to be the cation exchange capacity (c.e.c.) of the soil, losses decreasing with increasing c.e.c., and drying of the soil after applying urea to the surface, which increases losses. Aeration of an alkaline solution of ammonium salts increases the removal of ammonia so that wind will also increase losses from surface-applied slurry and faeces and urine voided by grazing animals. In the systems investigated by using pure urea, nitrite tended to accumulate at alkaline pH, whereas nitrification is most rapid and proceeds readily to nitrate at or near pH 7. Nitrite is undesirable because it is both toxic to plants and liable to loss by denitrification.

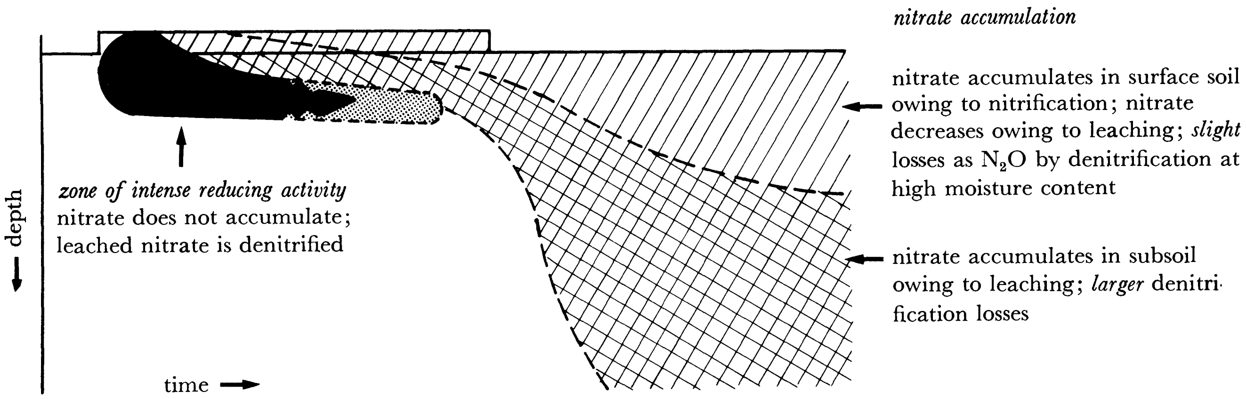

Figure 5. Diagram illustrating the pattern of nitrate accumulation and loss after a heavy slurry application. (Reproduced with permission of the Controller of Her Majesty's Stationery Office.) (Burford *et al.* (1976).)

In the field, Burford *et al.* (1976) applied cattle slurry at rates up to 550 t ha^{-1}. The slurry had 15.6% dry matter containing 2.15% N: the maximum rate applied was therefore 1845 kg N ha^{-1}. This may be compared with the 850 kg N ha^{-1} in dung patches and 450 kg N ha^{-1} in urine patches of cattle (Peterson *et al.* 1956). Slurry is a mixture of urine and faeces and the maximum rate used by Burford *et al.* is somewhat greater than the simultaneous voiding of urine and faeces at one point. Although excessive as a continuous dressing, the results provide useful information to develop a model to describe effects in the slurry layer and in the soil underneath.

Methane was evolved in the soil for several months after applying the slurry, indicating the presence of intense reducing activity at shallow depth. Nitrate initially present in the soil and slurry was lost by denitrification, and nitrate accumulation was inhibited for some time, either by poor aeration itself or by products resulting from restricted aeration. Aeration gradually improved with time from the slurry surface downwards, presumably allowing nitrification to proceed, and nitrate formed moved to the deeper soil layers. However, a zone of poorer aeration and intense reducing activity below the zone of nitrate accumulation resulted in further denitrification. Nitrous oxide was found in both of these zones after rainfall, confirming that denitrification was occurring and thus lessening the amount of nitrate leached during this time.

Similar conditions were used by Meijboom (1979) to remove N during the treatment of slurry from calves. Slurry was added and denitrification was allowed to take place; this was followed by a period of aeration for oxidation of ammonium to nitrite or nitrate. The balance between oxidizing and reducing conditions had to be carefully adjusted to obtain maximum removal of N as nitrous oxide and N_2. These processes are illustrated diagrammatically in figure 5 where the dotted area represents the zone preventing downwards movement of nitrate, and the shaded area represents the zone of intermittent or slow gaseous N loss depending on soil moisture. Losses of N as N_2O cannot be calculated accurately from observed concentrations in the soil atmosphere because of the difficulty in establishing transport rates between the source of production in the soil and the soil surface (Burford & Stefanson 1973). In addition to the need for assessments of the magnitude of N_2O production, there is also a need for measurement of losses as N_2, which may be the significant or dominant product in denitrification. Knowledge of the ratio of $N_2O:N_2$ in gases evolved from the soil may assist in interpretation of field data.

Table 5. NO_3-N in drainage water (milligrams per litre) from plots treated with slurry on 28 March 1972 (Burford *et al.* 1976)

date	slurry application rate/(t ha^{-1})				
(1972)	0	150	300	450	550
6 Dec.	4	7	10	20	27
7 Dec.	7	9	15	26	43
8 Dec.	7	12	14	18	56
10 Dec.	6	10	12	16	59
12 Dec.	7	17	23	31	61
mean	6	11	15	22	49

Table 6. Mean concentration (milligrams per litre) of NO_3-N in rainwater, land drainage, river water and sewage effluent (Smith 1976)

	rainwater	river water	sewage effluent
[NO_3-N]	0.43	2.46	26.33

drainage from	stock density†	[NO_3-N]
hill land	0.62	0.67
lowland	0.86	5.46
	1.66	6.11
	3.98	7.20

† Expressed as dairy cow equivalent (d.c.e.) per hectare.

Analyses of the drainage waters 8 months after applying the cattle slurry showed that the concentration of nitrate increased with the amount of slurry applied (Burford *et al.* 1976). Table 5 gives the concentrations in December 1972 for the four plots with slurry and one without. These results show that, with slurry at 150 ha^{-1}, on two occasions out of five the nitrate concentration of drainage exceeded the W.H.O. recommended value of 11.3 mg NO_3-N l^{-1} and with slurry at 550 t ha^{-1}, concentrations were two to five times this value. These effects were paralleled in a study of the effects of increasing intensity of livestock farming the catchment of the River Main, Co. Antrim, on the nutrient budget (Smith 1976); results in table 6 show how an increase in stock rate expressed as dairy cow equivalents (d.c.e.) from 0.62 d.c.e. ha^{-1}

to 3.98 d.c.e. ha^{-1} progressively increased the NO_3-N in the drainage water from 0.67 to 7.2 mg NO_3-N l^{-1}, compared with 2.46 mg NO_3-N l^{-1} in river water and 26.33 mg NO_3-N l^{-1} in sewage effluent.

Losses by leaching of nitrate

Nitrate lost by leaching depends on the water content and water-holding capacity of soils and on the amount of water moving through the soils. Several models for predicting nitrate movement in soils have been published. Burns (1977) proposed a simple mathematical model that assumes that nitrate movement from a layer of soil only occurs when the field capacity is exceeded and is directly proportional to water movement.

The validity of the leaching equation was tested by using experimental results on soils ranging from a sand to a clay, where good agreement was found between the model and experimental data.

In another model of nitrate movement in soils, Wild & Babiker (1976) found that on bare fallow plots given high rates of nitrate, the depth of the peak concentration of nitrate was correlated with the apparent depth of movement of the winter rainfall calculated as Q/θ, Q being the amount of effective rainfall (total rainfall minus evaporation), and θ the volumetric water content of the soil. The recovery of nitrate in the top 50 cm of the soil profile at the end of winter also varied with Q/θ, although no movement apparently occurred until there had been a minimum of 20 cm through drainage.

The movement of nitrate beyond the rooting depth of plants is important agriculturally because it represents a loss of available N, and movement into surface and groundwaters is important environmentally. Movement into the deeper aquifers has also been studied. The interpretation of nitrate profiles with depth is more complicated but is receiving much attention. Work by the Water Research Centre, reported by the Royal Commission on Environmental Pollution (R.C.E.P. 1979, p. 99 *et seq.*), has indicated that the form of agriculture, whether arable or grassland, has a major influence on the amount of nitrate entering the groundwater. In particular there is evidence that ploughing grassland or leys results in a burst of nitrate into the percolating water. The fertilizer and manuring régimes also affect nitrate entering the groundwater, as does the presence of legumes in the cropping sequence.

Losses as nitrous oxide and N_2

The production of nitrous oxide in soils was studied by Arnold (1954) nearly 30 years ago. Recent developments in analytical techniques for estimating small concentrations of gases and the development of isotopic analysis and of nitrification inhibitors have enabled very sensitive and exact measurements of processes to be made and followed.

Recently Bremner and his coworkers (Blackmer *et al.* 1980; Bremner *et al.* 1981) published information on the formation of nitrous oxide during the nitrification of ammonium sulphate under controlled conditions in the laboratory and of anhydrous ammonia injected into soil in the field. Figure 6 shows that in the laboratory the amount of nitrous oxide evolved was related to the amount of ammonium sulphate added. In this experiment 1 ng g^{-1} or less of nitrous oxide was evolved from the untreated soil, in the presence of nitrification inhibitor, or when N was added as nitrate. Figure 7 shows that nitrous oxide was evolved in the field from the untreated soil, a little more from anhydrous ammonia injected into the soil in the presence of a nitrification inhibitor and considerable amounts when anhydrous ammonia alone was injected into the soil. These results suggest that it is now possible to quantify losses of N as nitrous oxide during the nitrification of ammonium, and to assess the effects of agricultural practice on losses from the farming system and increased inputs to the atmosphere.

Denitrification has received much attention for many years and has been reviewed from time to time (e.g. by Broadbent & Clark (1965), Delwiche & Bryan (1976) and Garcia (1975)). In soils the end products of denitrification are almost entirely nitrous oxide and N_2, although some nitric oxide may occasionally be formed ephemerally. Conditions favouring denitrification are a lack of oxygen or very low oxygen tensions, the presence of a readily decomposable organic substrate, a temperature of 25–50 °C, and a neutral or slightly alkaline pH.

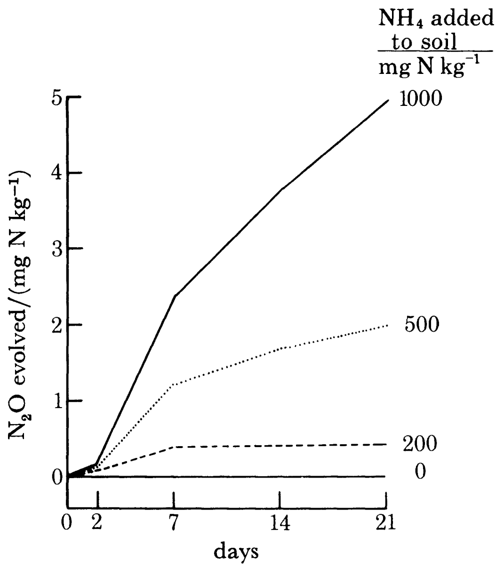

FIGURE 6. Nitrous oxide evolved from soil incubated at 30 °C with and without added ammonium sulphate. (Blackmer *et al.* (1980).)

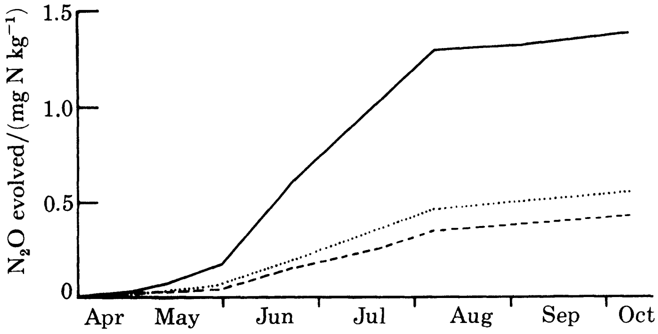

FIGURE 7. Nitrous oxide evolved in the field: ---, from soil alone; ——, with anhydrous ammonia injected; ..., with anhydrous ammonia and nitrification inhibitor. Anhydrous ammonia supplied: 180 kg N ha^{-1} (Bremner *et al.* (1981).)

A SIMPLE ENERGY SYSTEM FOR NITROGEN

There is no evidence to suggest that the total amount of N in the soil–plant system in agriculture is increasing, and with the larger arable acreage of the last 30 years the total mass of N in the soil has probably declined. One upward trend is that increasing afforestation leads to an increase in the mass of N in the biomass. Figure 8 shows a simplified nitrogen system for agriculture, by means of energy flows. Energy as imported food, imported feed, fertilizer N and fertilizer P and K for legumes adds to the total stock of N and increases the amount in circulation. Therefore the losses from the system must be at least as large as the known inputs; although little of this N will appear directly in the atmosphere or surface or groundwaters, most will leave the agricultural system after one or more changes or subsidiary cycles. One of the most important tasks at present is to quantify the movement of N through these various pathways and so assess the impact on other environments. Subsequently, an understanding of the processes may allow the losses from the system to be minimized, thus improving the utilization of N in farming, saving energy and reducing effects on the atmosphere and water.

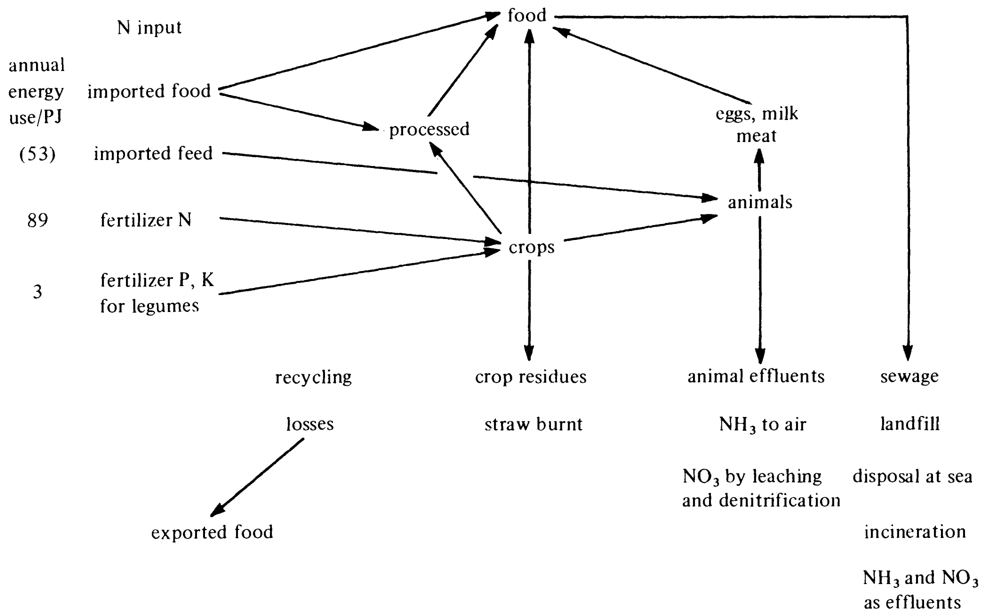

FIGURE 8. A simplified scheme for the nitrogen inputs to agriculture, their use in food production, recycling and losses.

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Discussion

J. V. Lake (*Agricultural Research Council Letcombe Laboratory, Wantage, U.K.*). Dr Gasser referred to the interesting work by Bremner's group over the last decade, showing that N_2O is produced during nitrification. Could he please put the scale of this loss into perspective compared with the other components of the N budget of arable crops?

J. K. R. Gasser. The results of Bremner's experiments given in figures 6 and 7 indicate that, under conditions favouring nitrification and therefore losses as N_2O, about 0.5 % of the added ammonium was lost as N_2O. There is no substantial information on the likely range of losses from different soils under various climatic conditions. This 0.5 % may be compared with losses by leaching of nitrate, commonly ten times as great, and unknown potential losses by denitrification. About half the added fertilizer N is frequently found in harvested crops.