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NITROGEN IN AGRICULTURE: AN OVERVIEW AND DEFINITIONS OF NITROGEN USE EFFICIENCY

by

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ABSTRACT.

The increased use of nitrogen (N) fertilisers in agriculture in the last five decades is justified by the increased yield potential of the crops grown and the judicious use of agrochemicals to control weeds, pests and diseases to protect that potential. Nitrogen use-efficiency can be assessed in a number of ways, discussed here with examples, but is usually determined as percent recovery of added N in the harvested product when calculated by the difference method. Assessed in this way, N-use efficiency is frequently only about 50%. But N-use efficiency of applied N should include that taken up by to produce the above-ground plant, where N plays a vital role in photosynthesis, the fixation of carbon dioxide to produce sugars, and the root system, which takes up nutrients and water. The fate of this N after harvest is important, but the total amount in crop should be included in any estimate of percent recovery of applied N. Within the plant-soil system, the soil microbial population competes with the plant for fertiliser N applied to increase plant growth. Hence any fertiliser N remaining in the soil should also be included in an estimate of the fate of applied N. The use of ^{15}N-labelled fertiliser allows the fate of the applied N to be determined. At harvest up to 70%, and sometimes more than this, of the applied N can be accounted for in the above-ground crop and in the soil to 100 m. The fate of the N which is not accounted for should be a major research topic.

Optimising the use and recovery of N fertiliser applied at the recommended amount for the expected yield requires that no factor which is within the control of the farmer or grower should adversely affect yield. These include the control of weeds, pests and diseases of both the above-ground plant and the root system wherever possible. It is equally important to optimise soil conditions so that all crops grown in sequence benefit. Root growth and function should not be jeopardised by poor soil structure. Soil organic matter plays an important role in maintaining and improving soil structure. Inefficient use of N fertilisers can arise when there is a too little plant-available phosphorus (P) and potash (K) in the soil. One function of P is to promote root growth to increase the uptake of water and nutrients. Applied fertiliser N increases the number and size of individual plant cells and consequently the water content of the plant. To maintain cell turgor increased quantities of K are required and if not available dry matter is not produced. Examples of these important factors in ensuring N-use efficiency are given in the paper.

CONTENTS

Keywords: nitrogen, N-use efficiency, N recovery, soil P, soil K, soil organic matter, soil structure.

1. INTRODUCTION.

Two hundred years ago crop production per unit area of land was limited by the inherent yield potential of the crops being grown and the lack of plant-available nutrients in soil. During the first half of the 19th century nutrient availability could be increased by the application of simple chemical salts (fertilisers) that were becoming available commercially. Nitrogen (N) was available as ammonium sulphate , a by-product of town gas production by burning coal, and sodium nitrate was being imported into Europe from the natural deposits in Chile. Phosphorus (P) could be purchased as single superphosphate, containing water-soluble calcium dihydrogen phosphate, after J B Lawes at Rothamsted had patented a process for making it from insoluble phosphates in 1842. Potassium (K) was available as a mixed salt of potassium sulphate and chloride obtained by leaching ash from burned trees in iron pots, hence potash. The potash deposits in Germany started production in the 1860s. Salts of sodium (Na) and magnesium (Mg) were also available.

Many soils were so nutrient deficient that farmers gradually began to apply fertilisers. Field experiments in this period showed that many soils were acutely short of P and it is interesting that in the UK the use of P fertiliser exceeded that of both N and K until after the Second World War (Figure 1). The much slower increase in the use of N in the second half of the 19th century and the first half of the 20th century probably reflects the limited yield potential of the varieties of crops grown at that time. For example, in the Broadbalk experiment at Rothamsted, the yield of winter wheat given optimum fertiliser remained at about 2.5 t/ha until the mid 20th century.

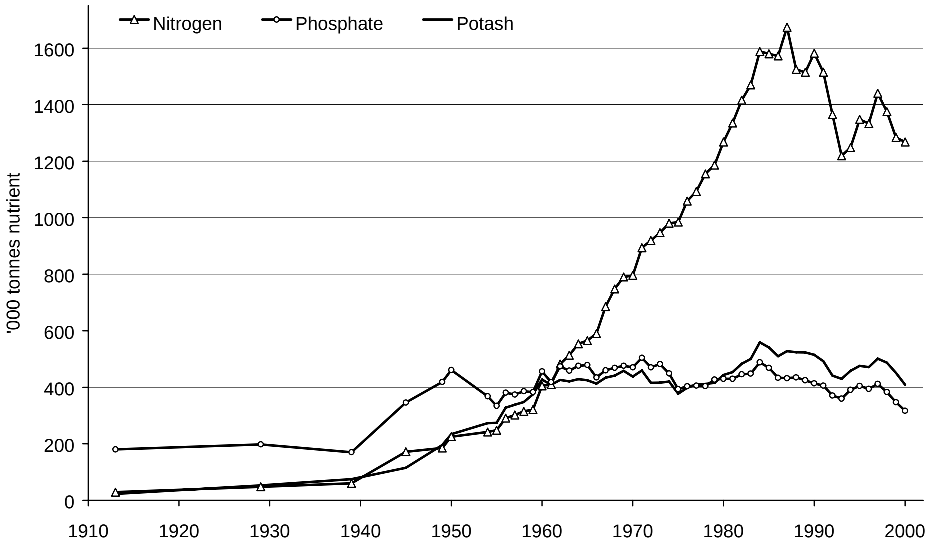

Figure 1: *Quantities of nutrients applied as fertilisers in UK agriculture, 1913 – 2000. (data from Rothamsted and AIC*).

The increased use of N fertilisers in the second half of the 19th century was sufficient for Sir William Crookes in his Presidential Address to the British Association in 1898, to warn that the world's known reserves of 'fixed' N (ammonium and nitrate) were being rapidly exhausted. This dire prediction was not realised because two methods of fixing atmospheric N were developed in the early years of the 20th century. In 1902, the commercial production of calcium nitrate by first combining nitrogen and oxygen was achieved by Birkeland and Eyde in Norway. This process was energy intensive and was soon replaced by the Haber-Bosch process developed in Germany for combining nitrogen and hydrogen. However, there was still no great increase in the use of N in agriculture (Figure 1) until after the Second World War when a number of factors came together. Plant breeders were introducing varieties of crops with a larger yield potential, fixed N was no longer required for munitions and the first agrochemicals were becoming available for the control of weeds, pests and diseases, any one of which could seriously decrease yields and limit an economic yield response to applied N fertiliser..

Thus it is only in the last 50 years or so that the efficient use of N in agriculture has become a topic of general interest and then largely because of the need to minimise any direct or indirect adverse effects of its use on the environment. It is equally important, however, to ensure that the money farmers spend on N as fertiliser or manure produces the largest possible financial return. This paper first briefly considers some of the developments in agriculture that have a bearing on nutrient use and then aspects related to N use efficiency in the production of crops for food, feed, fibre and bioenergy.

2. CHANGES IN CROP PRODUCTION AND UNDERSTANDING OF PLANT NUTRITION – THE NEED FOR FERTILISERS.

2.1. Agriculture before the 1800s.

Once mankind started to live in settled communities and till the soil to grow crops some 10,000 years ago, lack of plant-available nutrients in soil became the primary constraint to production. Attempts to overcome this problem are well illustrated by what happened in England. As in most of west and central Europe, perhaps 95% of the land in Britain was covered with woodland; it is now only about 20%. Initially the trees were cleared to allow shifting cultivation, but later large tracts of forest in Britain were also cleared to provide fuel in the early years of the Industrial Revolution. As population increased shifting cultivation gave way to the communal administration of land, the arable land in each village being divided between a few fields and a fallow-cereal and later a fallow-legume-cereal rotation was practised. To allow for lack of uniformity in soil fertility within a field, each was divided into strips, each strip being the area of land a man could plough in a day. Strips allocated to each villager were on 'better' and 'poorer' land in each field. The whole of a field would grow only one crop and each villager aimed to grow sufficient food to feed his family throughout the year. The few animals kept were grazed on common land.

In 1700, when the population was around 6 million, about 50% of the total arable land was held in open fields, which was socially advantageous because the villagers had to work as a community, but there was little incentive for innovation. From 1750-1830, about 21% of the 'open' fields and 'common' lands were enclosed by their owners, using the British Enclosure Acts, 1760-1830, to make small fields that were grouped into little farms often rented to tenant farmers. This gave these 'new' farmers the opportunity to introduce new crops and methods of growing them. Villagers who lost the use of land on which to grow their food migrated to the towns to become the labour force for the rapidly developing Industrial Revolution. By 1801, the population had increased to 11 million, mainly in the towns, and the food they required had to be produced by farmers developing a new capitalist business ethic.

Although the demand for food by the urban population was increasing, agricultural improvements occurred only spasmodically in the 1700-1800s. Jethro Tull (1674-1741) is credited with inventing the first 'modern' horse-drawn seed drill so that seed could be drilled in rows at constant depth to aid uniform germination. Later, he designed a horse-drawn hoe to help keep the inter-row land free of weeds and he improved the design of the plough.

Cereals, mainly for human consumption, were well established in English agriculture before the Romans arrived but they probably introduced grain legumes. In the mid 17th century, turnips, as a fodder crop for animals, potatoes and red clover were introduced into Britain and grown certainly in East Anglia, especially in Norfolk, by the landowners Viscount Townshend (1674-1738) and the 1st Earl of Leicester – Coke of Holkham (1754-1842). It was there that the Norfolk 4-course rotation of arable crops was introduced:

Turnips, spring barley, clover or grain legume, winter wheat

This rotation became the backbone first of English then European agriculture. It allowed animals to be kept during the winter fed on turnips and barley straw and bedded on wheat straw so that farmyard manure (FYM) was produced and applied to the land growing turnips. The legume fixed some N that benefited the following wheat. Only barley and wheat grain together with milk and meat were sold off the farm so nutrient losses from the farm were small. Phosphorus and K were available from the weathering of soil minerals and the mineralisation of soil organic matter (SOM). The small amounts of P and K released annually were probably sufficient to produce crops whose yield was limited by yield potential and by lack of available N in the soil. This system would not have been sustainable in the long-term because it was dependent on the availability of soil nutrient reserves (Johnston, 1991). The situation began to change in England with increased imports of animal feed and thus the import of N, P and K, part of which was added to the land in the larger amounts of FYM produced. The possibility of increased sustainability for this pattern of farming in Britain (and other European countries) was being achieved, however, by the depletion of soil nutrient reserves elsewhere.

2.2. The period 1800 – 1900.

By the early 1800s, the consensus view was that plants derived their carbon (C) from carbon dioxide in the air and hydrogen (H) and oxygen (O) from water taken up by roots from the soil. Following the meticulous research of de Saussure the relative proportions of the 'mineral' elements in plants was also known. Mineral elements, for example, P, K, Mg, calcium (Ca), silicon (Si) and chlorine (Cl), were those found in the ash of plants and were also known to be present in FYM, then the main source of nutrients for addition to soil. There was uncertainty about the source and importance of N, present in both plants and FYM, but not in plant ash and therefore not at that time considered a 'mineral' element. This ambiguity about the 'classification' of N was to create problems.

From the 1820s, Professor C. G. Daubeny held the chairs of Chemistry, Botany and Rural Economy at Oxford University, indicative of the level of interest in science at Oxford (and elsewhere) at that time! Importantly though, his researches there ended a very barren period in agricultural science. One of his major research topics was alleleopathy – the effect of a proceeding crop on the following one. He also distinguished between 'active' and 'dormant' plant nutrients in soil (Daubeny, 1845) which later led Way (1850 and 1852) to develop the concept of ion exchange in soil to explain why soils could adsorb ammonia. At Oxford during the 1830s, Daubeny was stressing the need for experiments to understand the nutrient requirements of crops (Daubeny, 1842). J. B. Lawes, owner of a small agricultural estate at Rothamsted, near Harpenden some 40km north of London, was an undergraduate at Oxford in 1832-34. He attended lectures by Daubeny and either consciously or sub-consciously saw an exciting, challenging future and he chose it (Dyke, 1993). In 1842, Lawes patented a process for the manufacture of superphosphate and had a factory in London producing it in 1843. Keen to start experiments on the nutrition of crops and animals, Lawes appointed J.H. Gilbert, a chemist by training, to help set up and supervise appropriate experiments on Rothamsted Farm. Gilbert took up his appointment on 1st June 1843, now considered the start of Rothamsted Experimental Station (now Rothamsted Research).

2.2.1. Initial uncertainties about the source of nitrogen for plants.

Throughout the first half of the 19th century, there was uncertainty and controversy about the source of the N in plants. De Saussure (1804) had shown that plants did not assimilate gaseous N in the atmosphere. In a series of pot experiments, Boussingault (1838) showed that peas and clover could get N from the air while wheat could not and Dumas fully realised the importance of this distinction (Dumas and Boussingault, 1841). Later, pot experiments by Lawes, Gilbert and Pugh, (1861) were at that time perhaps the most convincing demonstration that plants could not assimilate gaseous N – a result that agreed with those from the field experiments at Rothamsted – however, they did not explain why leguminous plants required no added N.

Returning from Oxford to Rothamsted in1834, Lawes in 1837 and 1838 tested different forms of N, as ammonium salts, applied to a cultivar of cabbage, used for animal feed, and turnips grown in pots and small plots on the farm (Lawes, 1842, 1843). Ammoniacal liquor from a gasworks was neutralised with appropriate acids, and the salts produced were all tested at the same rate of salt, i.e. different amounts of N were applied. In one experiment the yield of 25 cabbage plants given ammonium phosphate was 28kg, with ammonium sulphate it was 18kg and with ammonium chloride, nitrate and carbonate it was 13, 10 and 5kg, respectively. Ammonium phosphate containing less N than ammonium nitrate nevertheless gave the largest yield because it supplied P and soil was P deficient. Lawes concluded the second article by noting two very important facts.

- Applying ammonium salts to a soil deficient in P was useless – probably the first observation that N use efficiency depended on an optimum supply of another nutrient.
- Where the supply of minerals was adequate, the ammonia supplied by the atmosphere would be insufficient for the wants of a crop.

Lawes initial decisions about the design and treatments for the field experiments appear to have been influenced both by Daubeny at Oxford and Justus Liebig at Giessen in Germany. In England it was traditional, and in some cases mandatory, for farmers to grow arable crops in rotation – the Norfolk 4-course rotation. Probably influenced by Daubeny's work on the effect of one crop on a succeeding crop, Lawes decided that each of the important arable crops would be grown year after year in the same experiment (Lawes and Gilbert, 1895). For example, an experiment on turnips on Barnfield was started in June 1843, on winter wheat on Broadbalk in autumn 1843 and on spring barley on Hoosfield in spring 1852. The treatments initially were a control and FYM, others were based on Lawes' experience of the need to supply P, but also on the assertion by Liebig in 1840 on the need to supply the mineral elements (Liebig, 1840).

In the first year of the two Rothamsted experiments there were few tests of N, 8 of the 23 plots on Barnfield and 5 of the 21 plots on Broadbalk, and the maximum amount tested was only15 kg/ha (Johnston, 1994). The effect of N on the yield of turnips on Barnfield was far from clear. The method of drilling the fertiliser below the seed brought the two into close proximity and the osmotic effect of the salt impaired germination – still a possible problem today with band drilling of fertilisers. Where plants with N survived when given N they were individually larger than plants without N but the overall effect of N on yield was very small because plant population was diminished. By contrast, the winter wheat on Broadbalk responded well to the very modest application of readily available N. Compared to the unmanured crop, minerals alone increased yield by 19%, minerals plus N by 35% (Table 1). Lawes and Gilbert were quick to appreciate the significance of the result. For the next wheat crop drilled in autumn 1844, N was tested on 14 of the 21 plots and at four rates, 12, 24, 36 and 48 kg N/ha (Table 1).

Lawes and Gilbert never failed to stress the importance of supplying readily plant-available N, i.e. nitrate and ammonium, *provided that P was not*

limiting, for crops other than legumes. Equally important, their results soon showed that crop yields could be maintained by the application of plant nutrients in readily available inorganic salts if the large amounts if FYM they tested (35 t/ha applied cumulatively each year) were not available. Lawes and Gilbert never said that fertilisers were better than FYM. Like Malthus (1798), who urged that population increase should be checked when it was faster than the means of subsistence, Lawes and Gilbert also realised that at a time of a rapidly increasing urban population there would never be enough FYM to grow the large crops required.

Table 1: *Treatments tested and yields of winter wheat on Broadbalk, Rothamsted in 1844 and 1845*[a].

1844			1845		
Treatment	**Yield, t/ha**		**Treatment**	**Yield, t/ha**	
	grain	straw		grain	straw
None	1.03	1.25	None	1.62	3.04
FYM, 35 t/ha	1.43	1.65	FYM, 35 t/ha	2.20	4.39
FYM ashes	0.99	1.24	Minerals only	not tested	
Minerals only	1.12	1.29	Minerals + 24 kg N/ha	2.10	4.10
Minerals + 14 kg N/ha	1.43	1.59	Minerals + 48 kg N/ha	2.23	4.56
			Minerals + 72 kg N/ha	2.30	4.66

[a] The winter wheat was sown the previous autumn

2.2.2. Developing understanding of the nitrogen requirements of plants.

Stepping back a little to 1840, Justus von Liebig, a very well respected chemist, working at Giessen in Germany, was asked by the British Association for the Advancement of Science to prepare a report on 'Chemistry in its Application to Agriculture and Physiology'. The report was presented at the Association meeting in Glasgow in September 1840 and it appeared as a book later that year (Liebig, 1840). Besides stressing the need to supply mineral elements, Liebig discussed how plants acquire their N as ammonia from the soil, from manure and from the atmosphere. He continued by suggesting that atmospheric inputs of ammonia were not sufficient for the purposes of agriculture and he continued with this assertion in the second edition of the book in 1842. The early results from the Broadbalk experiments (Table 1) supported this view, namely that the 'natural' supply of ammonia was not sufficient for the purposes of agriculture, because applying small amounts of ammonium salts increased the yield of winter wheat.

Then, strangely, in the 3rd edition of his book in 1843, Liebig changed his mind and noted that, the quantity of N as ammonia from the atmosphere was sufficient for the purposes of agriculture. Based on the results from their field experiment, Lawes and Gilbert could not agree with this change and they took issue with Liebig. The arguments between Lawes and Gilbert at Rothamsted and Liebig in Germany took place in the scientific literature of the time and continued for some 20 years (Johnston, 1990). In retrospect, it is clear that the controversy was bedevilled by lack of an agreed nomenclature in a developing science. Eventually Liebig used an argument, suggested at a BA meeting in 1854, that ammonium salts were minerals. In 1862, he repudiated the classification of the ash constituents of plants as unscientific and claimed that he had always considered ammonia and its salts to be mineral manures (Liebig, 1862). Thus by analogy with other mineral elements, ammonium would be taken up by roots from soil.

In the discussions on the source of N for plants in this period it is perhaps a little unexpected that no link was made with another well-established process. In the 17th and 18th centuries nitrates required for the manufacture of gunpowder were produced in nitre beds from decaying animal and vegetable matter. Nobody appears to have suggested that in soil the decay of plant and animal remains could produce nitrate as a source of N for plants. In 1855, Lawes and Gilbert started to compare sodium nitrate with ammonium sulphate on Broadbalk and showed that both salts were equally effective as a source of N for plants. It was not until the mid 1860s that the importance of nitrification to soil fertility was recognised. Subsequent work established the importance of bacteria in N cycling. Schloesing and Müntz (1877) showed that the ammonia in sewage water was converted to nitrate. Warrington (1878, 1879) showed that nitrification in soil was stopped by adding chloroform, and that ammonium, in a solution of its salts, could be nitrified by adding a small amount of soil. He also showed that nitrification was a two stage process, nitrite and then nitrate being produced by two separate organisms, but it was not until 1890 that Winogradsky succeeded in isolating the organisms (Winogradsky, 1890).

The N nutrition of legumes was solved by the sand-culture experiments of Hellrigel and Wilfarth (1888). They showed that peas took up N from the atmosphere and that N assimilation was by 'a factor that occurred by chance' in their experiments. This factor was the development on the roots of nodules containing bacteria that could assimilate gaseous N. The bacteria was isolated by Beijerinck (1890) and called *Bacterium radicicola,* now known as *Rhizobium.*

3. THE NITROGEN CYCLE.

In terms of the evolutionary development of life forms on planet earth, neither plants nor animals can assimilate free nitrogen in the atmosphere to produce the nitrogenous compounds that are essential constituents of all living cells. The process of converting atmospheric N to useful nitrogenous compounds can occur in three ways. Lightening can provide sufficient energy to combine N and O to form NO_2, which when dissolved in rain to form HNO_3 is

transferred to soil. The amounts are small relative to those in the N cycle. Biological fixation of N by microorganisms, and industrial processes that fix atmospheric N are much more important. The N compounds in plants and animals are eventually decomposed and the N returned to the atmosphere. The fixation of free N and its eventual return to the atmosphere is called the N cycle. Putting the term 'nitrogen cycle' into 'Google' brought up 2,350,000 references in 45 seconds, such today is its perceived and actual importance. Developing ever more complicated written and visual depictions of the N cycle seems to have become something of a minor industry!

Nutrient recycling is essential for the sustainability and productivity of all natural ecosystems. To increase crop production to achieve economic optimum yields requires inputs of nutrients, especially of the major plant nutrients N, P and K. Some knowledge about and understanding of the nitrogen cycle is an essential step in improving N-use efficiency in agriculture. Because it is a cycle, discussion about inputs to and outputs from the cycle can start at a number of points. Early work concentrated on what happens in soil and current estimates of fertiliser Nuse efficiency are dependent on soil processes.

Liebig, in 1840, described a very simple N cycle. He noted that as plant and animal remains decompose in soil, ammonia is released and this escapes to the atmosphere from where it is returned to the soil in rainfall to be again taken up by plants (Liebig, 1840). Some 85 years later, Russell (1927) discussed the C and N cycles in so far as knowledge had increased by then. He also placed both cycles in the context of the decomposition of plant residues, animal remains and other similar organic materials like sewage sludge. Decomposition produced nitrates and/or gaseous nitrogen together with carbon dioxide (CO_2, which effected various changes in soil). Mineral elements were released and the end product was humus (soil organic matter). Russell wrote that there was good reason to suppose that the changes were in the main brought about by micro-organisms but there was no direct evidence for this at that time. He provided a more complex N cycle than that of Liebig (Figure 2).

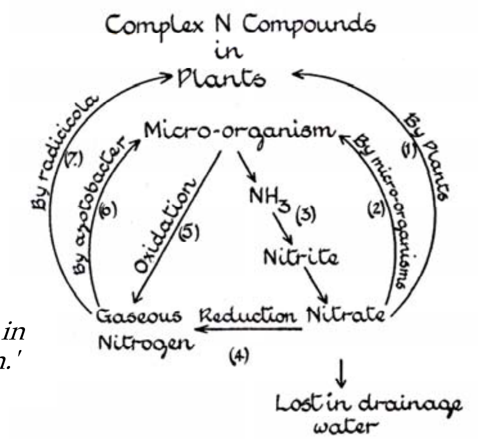

Figure 2: *'Scheme showing decomposition of plant residues in soil, so far as is at present known.' (Russell, 1927).*

By the 1950s, discussion about the N cycle tended to focus on the production of ammonia and nitrate, the forms of N taken up by plants, and by the microbial decomposition of organic compounds containing N. For example, Russell (1950) discussed the steps in the decomposition of organic N compounds in SOM or added organic manures and the bacteria responsible. Factors controlling the level of mineral N in soil were discussed as was the loss of nitrate from soil. At a time when little fertiliser N was used the importance of symbiotic N fixation by legumes and their contribution to the supply of plant-available N to other arable crops and grass was fully recognised. In soils sown to permanent grass, the gain in total N in soil was used to illustrate effects of symbiotic, and possibly non-symbiotic, N fixation using data from Rothamsted (Russell, 1950) and Johnston *et al.* (2008) have recently updated this data (Figure 3). Accumulation of N in soil is related to the increase in SOM, and Figure 3 shows that this occurs only very slowly even when soils with small amounts of SOM are sown to and kept in permanent grass.

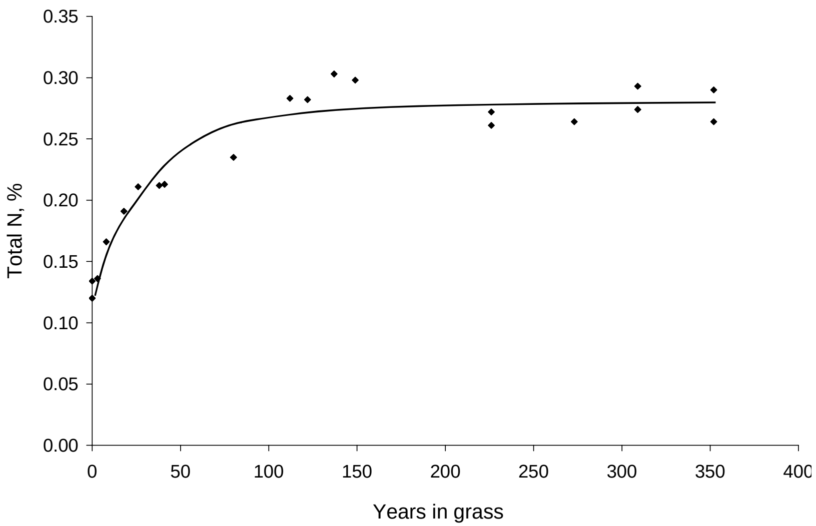

Figure 3: *Build-up of organic nitrogen in the top 23 cm of a number of silty clay loam soils sown to permanent grass at various times and for various periods at Rothamsted.*

More recently in a review of agriculture and the N cycle, Mosier *et al.* (2004) placed emphasis on the input of N fertilisers to the N cycle and the efficient use of these fertilisers, including the environmental impact of N losses from the system and how these might be mitigated. The N cycle these authors used is in Figure 4.

Representations of the N cycle are useful in showing the different components of the cycle and the pathways between them. However, it is even more important to put in numbers, i.e. amounts of N in the components and in the

pathways if the N cycle is to be fully understood and N use efficiency improved. Figure 4 has some numerical data for some parts of the cycle. Perhaps one of the most studied experiments is the Broadbalk experiment on winter wheat at Rothamsted. The amount of N in most components and pathways is known with some accuracy (Figure 5, overleaf) but in terms of possible environmental impact little is known about the amounts of N not accounted for by emissions to the atmosphere and loss of nitrate in drainage.

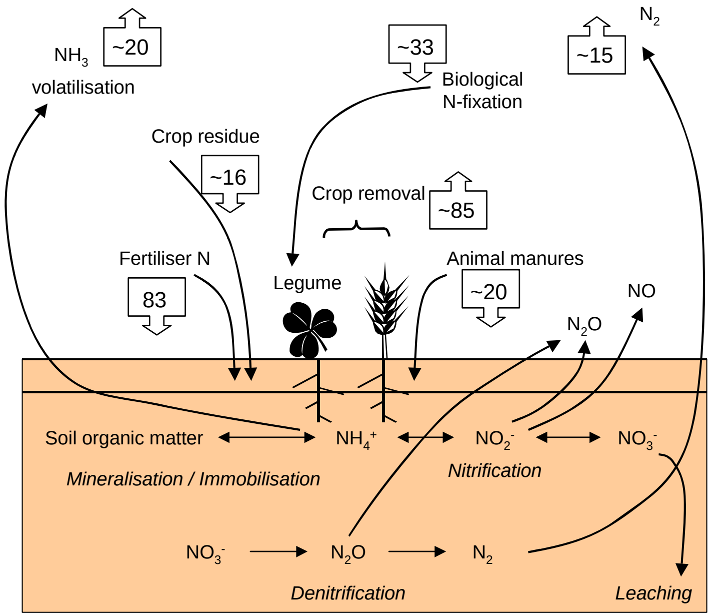

Figure 4: *A simplified nitrogen cycle for crop production systems. Estimated global nitrogen flows, in million tonnes, from Smil (1999), (adapted from Mosier et al., 2004).*

4. THE ROLE OF NITROGEN IN CROP PRODUCTION.

The primary processes involved in growth and dry matter production, such as photosynthesis and protein synthesis, upon which final yield depends, occur in individual cells and tissues. Structurally cells are quite simple but the functions they perform are extremely complex and often highly specialised in the economy of the plant. Individual cells can be visualised as having an expandable wall enclosing a central space, the vacuole, containing an aqueous solution. The vacuole is largely composed of water and it acts as a 'general storage compartment' for nutrients like P, K and Mg (as ions) and other solutes like sugars. The vacuole of a mature cell comprises more than 80-90% of the total cell volume and thus most of the plant's water is contained in the vacuoles.

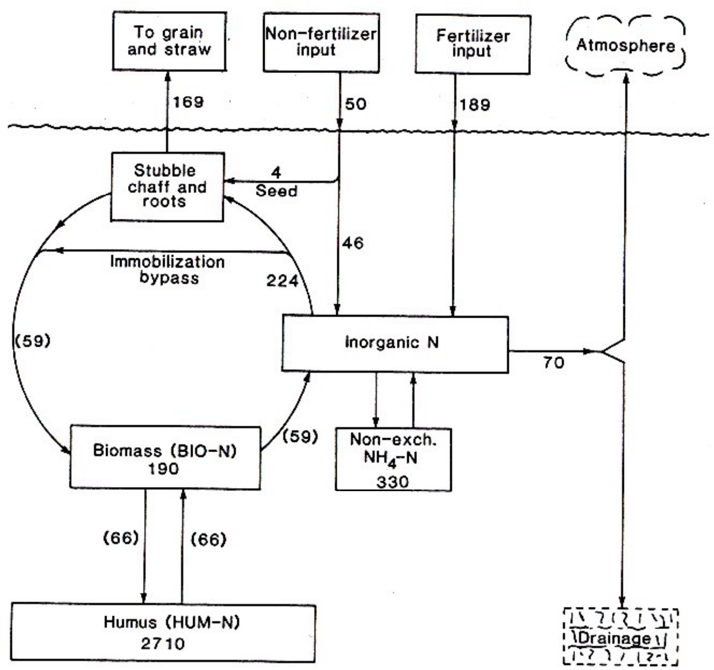

Figure 5: *Nitrogen cycle under continuous winter wheat receiving 144 kg N/ha every year, Broadbalk, Rothamsted. (for details see Powlson et al., 1986).*

One major determinant of growth and a prerequisite for large yields in most arable crops is the rapid expansion of the leaf canopy in spring which allows it to fully capture sunlight energy required to convert carbon dioxide to sugars which are then converted to other compounds constituting crop dry matter. Nitrogen is the major driver of leaf canopy expansion which it does by increasing cell division and cell expansion. This large N-induced increase in cell number and volume and the consequent increase in the amount of water in the plant requires a corresponding increase in the uptake of K and this is discussed later.

4.1. Crop nitrogen demand and nitrogen supply.

Maximum N uptake of winter wheat yielding 10 t/ha grain is of the order of 240 kg/ha and a rule-of-thumb maximum daily uptake rate to achieve this total uptake is 5 kg/ha (Barraclough, 1986a, b). About the same daily N uptake rate is required by winter oilseed rape and potatoes but it is somewhat larger for sugar beet. To ensure that this daily uptake rate can be maintained a large quantity of plant-available N must be present in the soil to drive the processes transporting plant nutrients to roots. These processes are mass flow and diffusion. The latter is a highly efficient transport process with the potential to supply nutrients at a far faster rate than mass flow.

It is possible to set target N concentrations in a saleable product to meet appropriate quality criteria, e.g. %N in wheat grain for a bread making wheat and %N in barley grain to meet criteria for malting. However, it has proved very difficult to define an N concentration in the vegetative part of the crop during growth to achieve the required N concentration in the grain at harvest. For cereals, %N in the dry matter of leaves and stems declines during growth as dry matter accumulates. Leigh and Johnston (1985) monitored %N in the dry matter of spring barley at three day intervals from emergence to harvest in four experiments where the crop was grown with and without N, with and without adequate PK, and with and without water stress. In all cases %N in dry matter declined throughout growth, but at different rates in individual crops depending on treatment. Grain yields at harvest ranged from 2 to 6 t/ha. While it would be possible from this data to relate an N concentration at a specific stage of growth to final grain yield, the data would be very growth stage specific. Consequently, much work would be required to get values which could be used for diagnostic purposes in commercial crops even if they were always sampled at the same growth stage. Leigh and Johnston (1985) also used this data set to see whether expressing N concentrations on a tissue water basis could be a reliable guide to N sufficiency. Earlier they had shown that expressing K concentrations in tissue water was a reliable guide to K sufficiency in the plant Leigh and Johnston (1983a, b). While spring barley grown with and without an adequate supply of K had different K concentrations expressed on a tissue water basis, N concentrations expressed similarly were the same at each stage of growth when grown with and without added N. Young plants had 8-10 g N/kg tissue water which declined to 3-5 g N/kg tissue water by anthesis. There was no evidence that N fertiliser consistently increased N concentrations in tissue water even though it increased growth rates and final grain yield. Thus N in tissue water cannot be used to diagnose N deficiency.

4.2. Acquisition of nutrients from soil by plant roots.

4.2.1. Root activity.

When there are sufficient nutrients available in the soil, from soil reserves or applied as fertilisers, to meet crop demand to achieve optimum yield, then the acquisition of these nutrients depends on both the distribution and activity of roots within the soil. Roots appear able to modify their uptake rates to meet demand. Kuhlman and Barraclough (1987) showed that, when either the nodal or seminal roots of winter wheat were removed, the remaining roots increased their rate of nutrient acquisition to meet the demand for shoot growth.

4.2.2. Root distribution.

There is much interest currently in root architecture in relation to the acquisition of nutrients by plants (Lambers *et al.*, 2006). However, particular attention needs to be given to the distribution of roots between surface soils, where most nutrients are usually found, and subsoils where plants may need to find water to sustain growth through periods of limited water availability in topsoil. Johnston and McEwen (1984) showed that the uptake of N by spring barley from small amounts of applied N was larger where subsoils had been loosened to 50 cm than after ploughing to only 23 cm. These authors assumed that there were more roots at depth following subsoil loosening and that these extra roots recovered nitrate, together with water, at depth in late spring. Although the difference in N uptake in this experiment would not in itself economically justify subsoil loosening, the result highlights the need for cultivation and soil management practices that enhance soil exploration by roots to find nutrients and water.

The adverse effect of a plough pan on crop yield due to its effect on root distribution can be considerable. The sandy loam soil at Woburn can have a compacted layer just below the plough layer (23 cm). In one experiment there was such a layer between 30 and 40 cm deep with a penetrometer reading of 35 bars and a bulk density of 1.8 g/cm^3. The subsoil was loosened with the Wye Double Digger to 50 cm and this had a major effect on root distribution (Figure 13 in Johnston *et al.*, 1998). On loosened soil, roots were present at 80-100 cm by December compared to just 40 cm on soil with the compacted subsoil. In the year this particular experiment was done there was ample rain after April and where N was not limiting the compacted layer had a negligible effect on grain yield (Barraclough and Weir, 1988). In drier years, McEwen and Johnston, 1979 and Johnston and McEwen, 1984) obtained larger yields of crops grown on soils where deep tillage had improved root distribution in subsoils.

5. RESPONSE OF CROPS, MAINLY CEREALS, TO NITROGEN.

Data from a number of experiments on crop response to N and other crop attributes associated with N fertiliser use are in Appendix Tables A-F to save repetition of treatments. Data are selected from these Appendix Tables to illustrate various aspects of crop response to N and the efficiency of N-use discussed in the following Sections.

5.1. Benefits from increased yield potential of wheat varieties.

It is generally accepted that there have been considerable improvements in the yield potential of many crops and the judicious use of agrochemicals to control weeds, pests and diseases has allowed the increased yield potential to be realised. In most cases improvements in crop yield potential have justified an increase in the application of N fertilisers. Grain yields with changes in the cultivar grown and the N applied in the Broadbalk Winter Wheat experiment at Rothamsted show how great the benefits have been over the last 140 years (Figure 6).

All plots grew winter wheat continuously from 1843 to 1967, then in 1968 the plots were subdivided to compare wheat grown continuously and in a rotation in which wheat follows a 2-year break to minimise the adverse effect of the soil-borne pathogen, *Gaeumannomyces graminis,* which causes take all. Where P and K have been applied during the experiment, plant-available P and K have

accumulated in soil and they do not limit yield. There have been some changes in the N treatments on plots getting P and K. The no N plot and those testing 48, 96 and 144 kg N/ha have been unchanged since 1852. In 1968, a test of 192 kg N/ha was started on a plot previously getting 96 kg N/ha. Then in 1985, a test of 240 and 288 kg N/ha was started on two plots that had received 96 kg N/ha either as ammonium sulphate or sodium nitrate. Until 1967 most plots had N as ammonium sulphate; from 1968 to 1985, N was applied as calcium ammonium nitrate c. 26%N, and since 1986 as ammonium nitrate, 34.5%N. Initially weeds were controlled by hand-hoeing or fallowing and since 1964 weedkillers have been used. Spring or summer applied fungicides have been used when necessary since 1979. The data in Figure 6 show just how much grain yields have increased as a result of these changes. Over the period from 1862 to 2000 maximum yields have increased about three-fold with most of this increase in the last 40 years. Without applied N, yields of all cultivars have changed little; they are about 1.5 t/ha. With 144 kg N/ha, the yields of both Red Rostock and Squarehead's Master were approximately doubled compared to the no N treatment. As was expected the change in 1968 to growing a short-straw variety, Cappelle Desprez, and increasing the amount of N to 192 kg/ha more than doubled maximum yield. Changing to Brimstone and then to Hereward have further increased yield. An outstanding increase in grain yield has come from introducing the 2-year break from wheat. In the recent period, 1996-2000, the yield of Hereward with 192 kg N/ha is 2 t/ha larger when grown in rotation than when grown continuously (Figure 6).

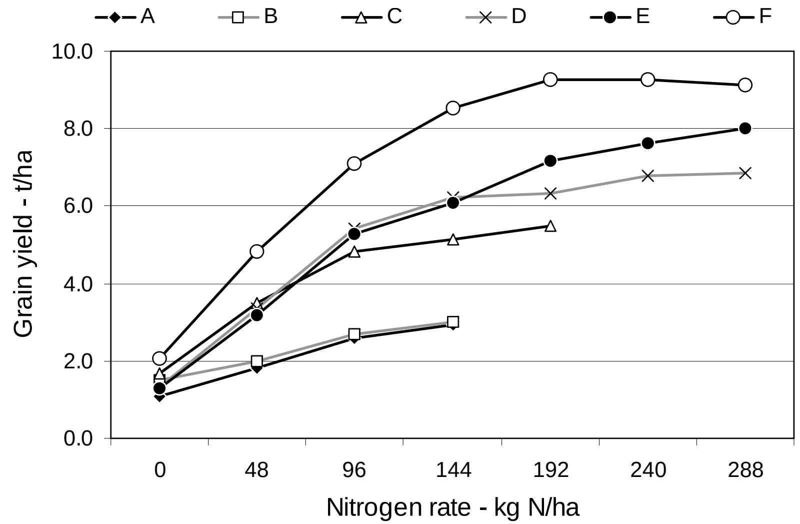

Figure 6: *Illustration of the increasing grain yields (at 85% DM) on Broadbalk Field at Rothamsted as wheat cultivars have changed.*

A = Red Rostock, 1862-1871.
B = Squarehead's Master, 1956-67.
C = Cappelle Desprez, 1970-78.
D = Brimstone, 1985-88
E = Hereward (continuous), 1996-00.
F = Hereward, (rotation), 1996-00.

5.2. Wheat grain yields and grain %N.

Grain protein in both wheat and barley is an important quality attribute. According to Miflin (1978), the factors of most importance in ensuring the production of cereals with a large protein content and satisfactory yield are availability of N (from soil and fertiliser) and redistribution of N to grain within the plant – in that order of priority. Benzian and Lane (1979, 1981) noted that grain %N for both winter and spring wheat increased almost linearly through the range of N applied while many of the yield response curves reached a maximum and then in some cases declined.

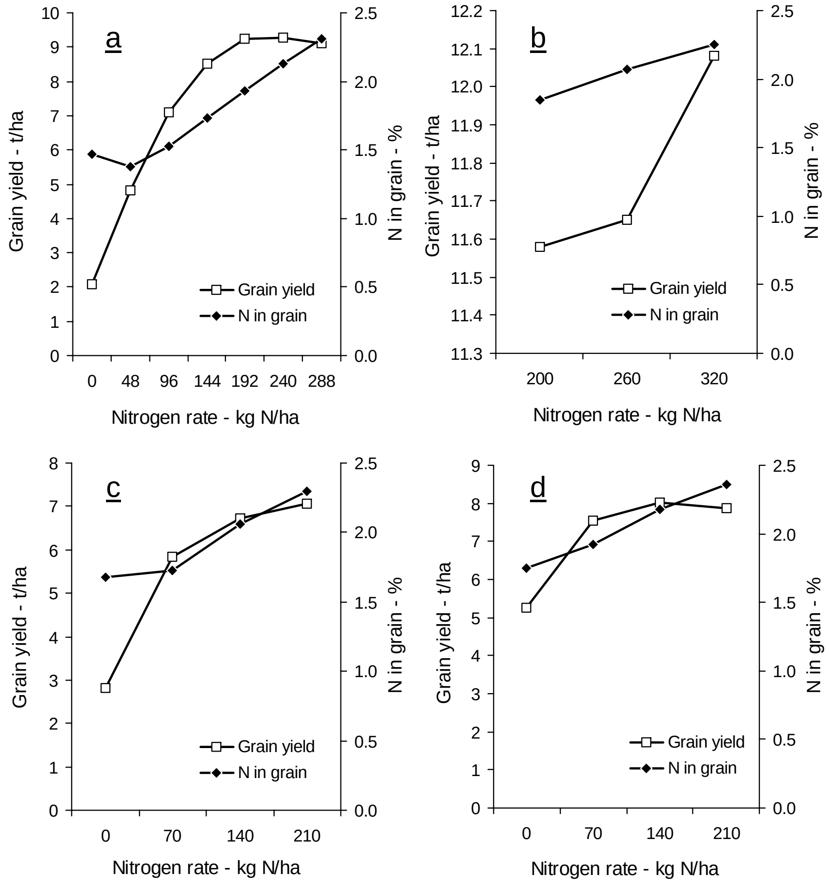

Figure 7: *Yield of winter wheat and grain N% with increasing amounts of applied nitrogen.*

7a: Continuous winter wheat, Broadbalk, Rothamsted, 1996-2000.
7b: 1st wheat after beans, Saxmundham RI, 2004-2006.
7c and 7d: Wheat grown in contrasted rotations, Woburn Ley-arable, 1981-2000.
7c: Wheat in an all-arable rotation following a break without wheat.
7d: Wheat following a grass-clover ley.

Figure 7 shows four relationships between N applied and the yield of winter wheat and grain %N and the effects of different crop management strategies. The different forms of the relationship can explain different aspects of N use efficiency by cereal crops discussed in Section 6. In this paper we have assumed that 13% protein (2.28% N) in wheat grain dry matter will be acceptable for a bread-making winter wheat other attributes required being acceptable.

Figure 7a shows the yield of cv. Hereward grown after a 2-year break in the Broadbalk experiment (from Appendix Table A). The yield response to applied N fertiliser was curvilinear, in this case yield reached a maximum and then declined a little. Grain %N decreased with the first increment of applied N, the well-recognised dilution effect, and then increased linearly. The dilution effect is when the increase in yield with a small amount of N results in a decrease in grain %N compared to grain %N in the crop grown on soil without N addition (Benzian and Lane, 1979, 1981). Hereward, like cvs Brimstone and Apollo grown since 1985, all had maximum grain yields in the range 8.3-9.3 t/ha when grown after a 2-year break but only achieved slightly more than 2.28 %N with 288 kg N/ha (Appendix Table A). Interestingly, the continuous wheat, which yielded appreciably less than wheat after a 2-year break, contained more than 2.28 %N when given either 240 or 288 kg N/ha.

Figure 7b (from Appendix Table B) shows yields and grain %N where three large amounts of N were applied in an attempt to ensure a grain protein content acceptable for a bread-making quality wheat together with an acceptable grain yield. Grain yields on the PK-treated soil ranged from 11.6 to 12.1 t/ha, only a small increase, but grain %N increased linearly from 1.85 to 2.25% N. The latter concentration achieved with 320 kg N/ha, the largest amount tested, was just below the 2.28% N standard.

Figures 7c and 7d compare winter wheat grain yields and grain %N averaged over a 20-year period in the Ley-arable experiment at Woburn (from Appendix Table C). Where wheat was grown in an all-arable crop rotation (Figure 7c) without applied N and little available soil N, the yield was just under 3 t/ha. With increasing amounts of N, yield increased to 7.1 t/ha with 210 kg N/ha but was only a little less (6.7 t/ha) with 140 kg N/ha. Following a ploughed-in 3- or 8-year grass-clover ley, both yields and grain %N were very similar and the mean is given here. The availability of N from the mineralisation of the ploughed-in, N-rich ley residues gave a yield just over 5 t/ha while 140 kg N/ha increased yield to 8.0 t/ha. Maximum yield following the ley was 1 t/ha larger than that in the all-arable rotation and less fertiliser N was needed to achieve it. Wheat grain %N in both the all-arable and ley rotation increased almost linearly; it was 2.30% N with 210 kg N/ha in the all-arable rotation and 2.36% N with 210 kg N/ha in the ley rotation.

6. DEFINING NITROGEN USE EFFICIENCY.

The outcome of any discussion about the recovery and efficient use of soil, fertilizer and manure N is partly dependent on the definitions adopted and whether crop yield or N uptake data are used. A large percentage recovery of added N is taken to imply an efficient use of N by the plant.

A number of agronomic indices and methods are used to measure the efficiency with which plant nutrients are used in agriculture. In summary, the methods and indices, based on those of Cassman *et al.* (1998), are:

1. Direct Method. This method can be used for N because the fertilizer can be labelled with the heavy isotope ^{15}N. Where fertiliser is labelled with ^{15}N it is possible not only to measure N in the crop during growth and in the harvested product but also the amount remaining in soil at harvest. The result is often expressed as a percentage. Experiments using ^{15}N are expensive and are not widely used but they do give the best estimates of N-use efficiency.
2. Difference Method. This method requires treatments in the same experiment with and without added N and the data can be used in two ways.
   - Using yield, $(Y_N - Y_0)/F_N$, where Y_N and Y_O, are the crop yields with and without N, respectively and F_N is the amount of N applied, all in kg/ha. This is frequently considered to be the 'agronomic efficiency' of applied N.
   - Using N uptake, $(U_N - U_O)/ F_N$, where U_N and U_O are the N uptake by crops with and without applied N, respectively, all in kg/ha. This is frequently considered to be the 'apparent recovery' or 'apparent efficiency' of applied N.

Results obtained by these two methods are often expressed as percentages.

Two other indices that are used sometimes are:

3. kg product produced per kg N applied Y_N/F_N (Y_N and F_N as above). This is often called the 'partial factor productivity' of applied N.
4. kg product increase per kg increase in N in the crop, $(Y_N - Y_O)/(U_N - U_O)$. (Y_N, Y_O, U_N and U_O as above). This is often called the 'physiological efficiency' of applied N.

Examples for methods (1), (3) and (4) of estimating N-use efficiency can be derived from the data in Appendix Tables A-F and are discussed following discussion of N-use efficiency determined using the direct method.

6.1. Direct method.

The efficiency of fertiliser N-use estimated by using ^{15}N (the direct method defined in 6(1) above) is illustrated by data obtained in an extensive series of experiments undertaken by Rothamsted and summarised in Tables 2, 3 and 4. These summaries are derived from data published by Powlson *et al.* (1986), Powlson *et al.* (1992), Macdonald *et al.* (1997) and Glendining *et al.* (1997).

The effects of season and soil type on recoveries, residues and losses of ^{15}N-labelled fertiliser applied to arable crops have been summarised by Macdonald *et al.* (1997). In each experiment the fate of the applied labelled N was determined in the above ground crop and in the soil either 0-23 or 0-100 cm. Care was taken to harvest as much as possible of the crop at harvest e.g. grain, straw, chaff and stubble of cereals. The labelled N in soil was either in root residues, soil organic matter or mineral N, the latter was usually a very small proportion of the labelled N in soil. From the recovery of labelled N in crop and soil, the amount of labelled N that was not accounted for was calculated but it was not possible to say how it had been lost.

Table 2 (overleaf) shows N-use efficiency by winter wheat in experiments at Rothamsted and Woburn. Best yields of wheat grown continuously on Broadbalk were a little less than 7 t/ha; wheat grown in rotation in this and other experiments yielded from 9-10 t/ha, except in the Intensive Cereals experiment at Woburn. Percent N recovery in the grain ranged from 31 to 66% and was not directly related to yield. Much more of the applied N could be accounted for (up to 80%) in the above ground crop at harvest and if the labelled N in the soil (0-23cm) was included percent recovery ranged from 71-91% (Table 2). Labelled N in the top 23cm soil accounted for up to 30% of that applied and tended to increase with the amount added. This does not necessarily imply an increase in total soil N because some of the labelled N could have replaced organic N mineralised during the growing season and taken up by the growing crop. The amount of labelled N not accounted for increased with the amount applied. Powlson *et al.* (1992) showed that there was a reasonable (r^2 = 0.73) relationship between rainfall in the three weeks following the application of labelled N fertiliser to winter wheat in spring and percent loss of the labelled fertiliser. Other loss process may be involved also. Attempts to increase N-use efficiency must seek to lessen the quantity of 'unaccounted for' N.

Table 2 also shows for this group of experiments the recovery of N in the above ground crop at harvest calculated by the difference method defined in Section 6(ii). Compared to percent N recovery determined using labelled N, those determined by the difference method are all much larger. All the soils in this group of experiments contained only small amounts of plant-available N and consequently, without applied N, there was little N in the above ground crop at harvest to subtract from the N in crop were N was applied. Also, percent recovery by the difference method in these experiments is much larger than that often found in agronomic experiments, for example values given in Section 6.2 that follows. This is because in these ^{15}N experiments so much care was taken to harvest all the above ground crop including small grains, chaff and stubble of cereal crops and this does not happen in most experiments.

In another series of experiments in 1987 and 1988, winter wheat and oilseed rape were grown at Rothamsted, on two soil types and at Woburn also on two soil types. Potatoes were grown on the silty clay loam at Rothamsted and the sandy loam at Woburn while sugar beet were grown only at Woburn on a

Table 2: *Recovery of nitrogen applied in spring as ^{15}N-labelled fertiliser to winter wheat in various UK experiments.*

N applied	Grain 85% DM	N in above ground crop kg N/ha			Labelled N in soil at harvest 0-23 cm	% recovery of labelled fertiliser N				Labelled N not accounted for	N recovery in above ground crop
kg N/ha	t/ha	Labelled	Unlabelled	Total	kg N/ha	In grain	In above ground crop	In soil 0-23 cm	In crop + soil	kg N/ha	Difference method - %
Winter wheat grown continuously, Broadbalk, Rothamsted, mean 1980-81. Silty clay loam soil.											
0	1.44	0	30	30		-	-	-	-	-	-
48	3.72	25	45	70	16	41	52	33	84	8	83
96	6.07	60	67	127	20	49	62	20	83	16	101
144	6.44	87	74	161	27	46	61	18	80	29	91
189	6.88	117	74	190	28	46	62	15	77	43	85
Winter wheat grown after a break crop in the multifactorial experiments, Rothamsted, mean 1980-81. Silty clay loam soil.											
0	7.02	-	117	117	-	-	-	-	-	-	-
213	8.98	132	136	268	34	35	62	16	78	47	71
Winter wheat grown after a break crop in the multifactorial experiments, Rothamsted, mean 1982-83. N applied as $K^{15}NO_3$.											
0	3.58	-	68	68	-	-	-	-	-	-	-
220	8.98	180	76	256	22	58	81	10	91	19	85
Winter wheat grown after a break crop in the Rotation II experiment, Saxmundham, mean 1981-82. Sandy clay loam soil.											
0	7.06	-	113	113	-	-	-	-	-	-	-
143	9.80	83	116	199	25	44	58	17	75	36	60
Winter wheat grown after a break crop in the Intensive Cereals experiment, Woburn, mean 1981-82. Sandy loam soil.											
0	0.64	-	25	25	-	-	-	-	-	-	-
146	3.19	89	37	126	27	31	66	18	84	24	69
Winter wheat grown following a ploughed in ley crop in the Woburn Ley-arable experiment, Woburn, 1984. Sandy loam soil.											
Following a grass ley given N, mean of 3- and 8-year leys:											
0	3.56	-	58	58	-	-	-	-	-	-	-
68	7.28	47	64	111	0	57	68	13	81	13	78
136	9.84	104	76	180	18	65	77	13	90	14	90
204	9.73	147	70	217	26	60	72	12	84	33	78
Following a grass-clover ley, mean of 3- and 8-year leys:											
0	6.63	-	105	105	-	-	-	-	-	-	-
68	9.40	52	105	157	7	64	76	10	86	10	76
136	10.40	106	112	218	16	66	78	12	90	14	83
204	9.50	145	101	246	29	58	72	14	86	28	69

sandy loam (Table 3). In these experiments there was a treatment without N only in the first of the two years to determine the natural abundance of ^{15}N (which varies little) to correct the data for the labelled N treatments in both years. Given here are the average data for the two years with the labelled N treatment. On each farm there were some differences in yield on the two soil types for wheat, oilseed rape and potatoes, but little difference in percent labelled N in the grain, seed, tubers or roots as appropriate and in the total N in crop plus soil. For winter wheat, percent recovery of the labelled N in the above ground crop tended to be lower than that in Table 2, probably because yields were less in 1987-88. Percent recovery of labelled N in the seed of oilseed rape was small, 20-29%, but it was about 50% in potato tubers. The amounts of labelled N remaining in the soil to 100cm were appreciable, ranging from 19 to 30 % of the amount of N added. The amounts of N not accounted for were also quite large probably reflecting less than expected yields for the amount of N applied.

Table 4 shows data for spring barley given three rates of labelled N when grown on soils with PK fertilisers and FYM at Rothamsted. The latter soil has received 35 t/ha FYM annually since 1852 and now contains about 2.5 times more SOM than the PK-treated soil. With each amount of added N, the yield of grain was larger (up to 1 t/ha) on the soil with more organic matter. At harvest, the amount of labelled N in the above ground crop and the soil increased with the amount of N applied and was almost identical on both soils. Consequently, the percent recovery of labelled N in above ground crop plus soil was the same as was the amount of labelled N not accounted for. This result is perhaps somewhat unexpected and indicates that the efficiency of fertiliser N-use was not adversely affected by the availability of large amounts of available N in the FYM-treated soil. When determined by the difference method, the recovery of added N in the above ground crop was much larger than that determined using labelled N. This was because the total N taken up by the crop given no N was small relative to the amount of N in the crop where N was applied.

6.2. Difference method.

Nitrogen use efficiency, estimated as percent recovery of applied N, can be determined by the Difference Method (Section 6(ii) above). This widely used method requires experimental treatments with and without added fertiliser N. The result is influenced not only by the amount of N applied but also by the yield achieved, which can be affected by extraneous factors like weeds, pests and disease, and by the management of the crop. As applied N increases yield decreases but grain %N increases, see examples for cereals in Figure 7. However, the increase in grain %N is not sufficient to prevent % N recovery decreasing with increasing amounts of applied N.

Table 5 (p 26) shows %N recovery of the wide range of amounts of N tested on winter wheat grown in the Broadbalk experiment. Only at the lower rates of N is % recovery in the grain a little better when wheat is grown in rotation. But when estimated in grain plus straw, % N recovery is slightly larger for crops in rotation partly because there is more N in straw in wheat grown in rotation.

Table 3: *Recovery of nitrogen applied in spring as ^{15}N-labelled fertiliser to winter wheat, oilseed rape, potatoes and sugar beet on contrasted soils in a number of experiments at Rothamsted and Woburn, UK, mean 1987-88.*

Crop, site and soil type	N applied	Yield	N in above ground crop			Labelled N in soil at harvest, 0-100 cm	% recovery of labelled fertiliser N				Fertiliser N not accounted for
			kg N/ha				In saleable crop	In total crop at harvest	In soil to 100 cm	In crop + soil	
	kg N/ha	t/ha	Labelled	Unlabelled	Total	kg N/ha					kg N/ha
Winter wheat, grain, Rothamsted.											
Silty clay loam	220	6.65	122	76	198	42	35	56	19	75	55
Chalky loam	221	5.80	123	67	190	54	34	56	24	80	44
Winter wheat, grain, Woburn.											
Sandy loam	174	4.02	86	35	121	42	32	51	24	75	44
Heavy clay	225	5.98	98	75	173	63	27	47	28	75	56
Oilseed rape, seed, Rothamsted.											
Silty clay loam	238	2.98	101	73	174	69	24	42	29	71	69
Chalky loam	235	3.84	110	71	181	66	29	46	28	74	61
Oilseed rape, seed, Woburn.											
Sandy loam	232	3.08	119	60	179	64	28	51	28	79	49
Heavy clay	236	2.54	94	77	171	70	20	41	30	71	68
Potatoes, tubers, Rothamsted.											
Silty clay loam	223	46.6	150	75	225	44	50	67	20	87	30
Potatoes, tubers, Woburn.											
Sandy loam	226	47.8	122	49	171	46	50	56	20	76	54
Sugar beet, roots for yield; roots and tops for total crop N uptake, Woburn.											
Sandy loam	122	48.7	74	72	146	32	27	60	26	86	17

Table 4: *Recovery of nitrogen applied in spring as ^{15}N-labelled fertiliser to spring barley grown in the Hoosfield Continuous Barley experiment, Rothamsted, UK, mean 1986-87.*

N applied	Grain yield 85% DM	N in above ground crop			Labelled N in soil at harvest	% recovery of labelled fertiliser N				Labelled N not accounted for	N recovery in above-ground crop
		kg/ha				In grain	In above ground crop	In soil 0-70 cm	In crop + soil		
kg N/ha	t/ha	Labelled	Unlabelled	Total	kg N/ha					kg N/ha	Difference method
Barley grown on soil with PK fertilisers.											
2	2.13	1	38	39	1	27	36	50	86	-	-
46	3.68	21	48	69	16	34	47	36	83	8	65
93	4.51	45	51	96	30	37	49	32	81	18	61
140	4.54	72	44	116	41	39	53	29	82	25	55
Barley grown on soil with FYM.											
2	4.84	1	115	116	1	27	36	34	70	-	-
46	5.56	23	127	150	13	35	50	27	77	10	74
93	5.72	46	122	168	31	34	50	33	83	17	56
140	5.20	70	97	167	42	34	51	30	81	27	36

Table 5: *Percent recovery of applied nitrogen fertiliser by winter wheat[a] on Broadbalk, Rothamsted. Calculated by the difference method.*

	N applied, kg/ha						
	0	48	96	144	192	240	288
Wheat grown continuously							
Yield grain, t/ha	1.29	3.18	5.28	6.10	7.16	7.62	8.00
% recovery in grain		50	61	56	59	57	51
% recovery in gr +st		56	70	63	68	66	61
Wheat grown in rotation							
Yield grain, t/ha	2.07	4.81	7.11	8.53	9.25	9.27	9.11
% recovery in grain		62	69	69	66	59	53
% recovery in gr + st		73	79	80	76	70	63

[a] winter wheat cv. Hereward, mean data for 1996-2000

Table 6 shows how % N recovery by wheat grain plus straw has increased as yields (Figure 6) on Broadbalk have increased. Squarehead's Master (1966-67) yielded little more than Red Rostock (1852-71) and % recovery of each amount of applied N was similar for the two varieties. Percent recovery by Hereward has doubled at comparable N rates.

Table 6: *Increase in percent recovery of nitrogen fertiliser in grain plus straw over time Broadbalk, Rothamsted. Calculated by the difference method.*

N applied	**1852 -71**	**1966 - 67**	**1996 - 2000**
kg/ha	Red Rostock	Squarehead's Master	Hereward
48	32	32	56
96	33	39	70
144	32	36	63
192	28	nt	68

nt = not tested.

Table 7 shows % N recovery by winter wheat grown in the Ley-arable (data from Appendix Table C) and the Organic Manuring experiments (data from Appendix Table F) at Woburn. In the Ley-arable experiment, the yield on plots without N and with 70 and 140 kg N/ha, was larger following the ploughed-in ley than in the all-arable rotation, but the applied N was used as efficiently in both rotations judged by % N recovery. In the Organic Manuring experiment, yields on the FYM- and ploughed-in ley soils were larger than on PK-treated soils with both 50 and 100 kg N/ha. Percent recovery of both amounts of N increased as yield increased suggesting that the presence of more soil N from mineralisation of organic residues did not adversely affect the efficient use of the fertiliser N.

Table 7: *Percent recovery of applied fertiliser nitrogen by winter wheat in two experiments at Woburn. Calculated by the difference method.*

		N applied, kg/ha			
Woburn Ley-arable		0	70	140	210
Wheat in all-arable rotation	Grain, t/ha	2.81	5.83	6.73	7.06
	% recovery in grain		64	56	47
Wheat in rotation	Grain, t/ha	5.26	7.55	8.02	7.88
	% recovery in grain		64	51	33
		N applied, kg/ha			
Woburn Organic Manuring		0	50	100	200
Wheat with PK fertilisers	Grain, t/ha	1.66	2.85	4.1	4.02
	% recovery in grain		36	38	24
Wheat with FYM	Grain, t/ha	3.99	5.63	6.46	7.06
	% recovery in grain		38	45	36
Wheat following 8-year ley	Grain, t/ha	4.83	6.76	7.44	7.09
	% recovery in grain		48	51	29

Table 8 (overleaf) shows % N recovery for spring barley. In the Ley-arable experiment, spring barley followed wheat and without added N the ley residues continued to give a larger yield than that in the all-arable rotation. However, the % N recovery was less when barley followed the ley than it was in the all-arable rotation suggesting that the mineralised N from the ley residues was used effectively by the barley. Interestingly however, where barley was grown continuously in the Hoosfield Barley experiment on PK-fertiliser and FYM-treated plots, although yields were larger on FYM-treated soil, % recovery of the fertiliser N was very similar on both plots. Why barley used mineralised N from ley residues in the Ley-arable experiment efficiently but not N from mineralisation of FYM in the Hoosfield experiment is difficult to understand.

Percent recovery of each increment of applied N is sometimes determined. On the steeply rising part of the yield response curve, %N recovery of each increment of N will be very similar but as the yield approaches the maximum, % recovery of each additional increment of applied N will decrease rapidly. This can be shown using data in Appendix Tables A to F.

Table 8: *Percent recovery of applied fertiliser nitrogen by spring barley in an experiment at Woburn and at Rothamsted. Calculated by the difference method.*

Woburn Ley-arable		**N applied, kg/ha** 0	60	120	180
Barley in an all-arable rotation	Grain, t/ha	2.29	4.56	5.41	5.14
	% recovery in grain		56	46	33
Barley in rotation with a grass-clover ley	Grain, t/ha	4.16	5.64	5.85	5.39
	% recovery in grain		45	34	22
Hoosfield Barley experiment		**N applied, kg/ha** 0	48	96	144
Barley on PK-treated plots	Grain, t/ha	1.95	4.00	5.15	5.68
	% recovery in grain		48	43	39
Barley on FYM-treated plots	Grain, t/ha	6.54	7.49	7.93	7.86
	% recovery in grain		46	38	30

6.3. Partial Factor Productivity.

Partial Factor Productivity (PFP), calculated as kg product per kg N applied, is shown for all experiments in Appendix Tables A to F. On the steeply rising part of the yield response curve, the PFP for each amount of added N is likely to be similar but as the yield approaches the maximum the values will decline. When excessive amounts of N are applied, the plant does not necessarily produce enough leaf area to synthesise sufficient carbohydrate to be translocated to the grain or irrespective of the amount of N applied the grain filling period is shortened for some reason.

6.4. Physiological efficiency of nitrogen use.

Physiological efficiency of N use for cereals is calculated as kg increase in grain per kg increase in N in grain; values are given in Appendix Tables A to F. This approach seems to have interest when applied to this data. As noted earlier, the factors of most importance in ensuring the production of cereals with a high protein content and satisfactory yield are availability of N (from soil and fertiliser) and redistribution of N to grain within the plant – in that order of priority (Miflin, 1978). Cereals will first use N to increase the leaf canopy by increasing cell number and cell size and the leaf canopy will set the rate of assimilation of sugars and the amount produced. In the early stages of growth the number of tillers and their survival will be determined and the number of grains per ear will be set. Yield will increase if there is sufficient assimilate to be translocated to this predetermined number of grains. Nitrogen taken up by the plant and not used in proteins will be stored in the plant mainly as RuBP carboxylate. During grain filling this N and that in protein will be re-mobilised to be translocated to the grains and converted to protein. Figures 7a, 7c and 7d show that the relationship between applied N and yield is curvilinear and linear for grain %N. A decline in kg increase in grain per kg increase in N in grain would suggest that the plant has put proportionally more N into the grain as protein with increasing applied N. This decrease occurs in almost all the examples in the Appendix Tables. While this is interesting it is difficult to see how it could be used as a diagnostic tool unless it was possible to determine some appropriate critical value.

7. SOME FACTORS AFFECTING THE EFFICIENT USE OF NITROGEN FERTILISERS.

7.1. Nitrogen demand and crop cultivar.

The greatly improved yield potential of many crop cultivars has increased the requirement for N (Figure 6), and this has changed the efficiency with which N is used at the smaller rates of application. Table 9 shows kg grain produced per kg N applied for three cultivars of winter wheat grown continuously on Broadbalk. There was little difference in the yield potential of Red Rostock (1852-71) and Squarehead's Master (1952-61) and at each level of applied N, kg grain per kg N applied was nearly the same. When Hereward was grown on the same plots with the same amounts of N in 1996-2000, kg grain per kg N applied was greatly increased, especially when the crop was grown in rotation. Much of the change in the production of grain per kg N applied in cereals is due the change in grain: straw ratio achieved by plant breeding. For all three cultivars, kg grain produced per kg N applied decreased as N applied increased.

Table 9: *Improvements in nitrogen use efficiency with cultivars with a larger yield potential, winter wheat on Broadbalk, Rothamsted.*

N applied	**kg grain per kg N applied**					
	Red Rostock	Squarehead's Master	Cappelle Deprez		Hereward	
kg/ha	1852-71	1956-67	1970-78		1996-2000	
			Continuous	Rotation	Continuous	Rotation
48	39	41	73	106	66	100
96	26	28	50	63	55	74
144	19	21	37	39	42	59

On Hoosfield Barley different cultivars have been grown with 48 kg N/ha throughout but with different PK treatments (Table 10, overleaf). For all three cultivars, grain yield with NP and NPK has always been larger than that with N alone or NK. Consequently kg grain per kg N applied has always been larger where P has been applied; N-use efficiency is increased by the presence of sufficient plant-available P in soil.

Table 10: *Improvements in nitrogen use efficiency with cultivars with a larger yield potential, Hoosfield Barley, Rothamsted.*

Treatment	N applied	kg grain per kg N applied		
		Chevalier	Plumage Archer	Optic
	kg/ha	1852-71	1952-61	2003-06
N	48	43	34	18
NK	48	46	36	24
NP	48	62	53	60
NPK	48	61	52	83

7.2. Soil Organic Matter.

For plants to acquire nutrients from soil, especially if they are required quickly to meet the rapid development of the above ground parts, they need to develop an adequate root system quickly. To do this requires a good soil structure, which in part depends on soil organic matter (SOM). The importance of SOM in improving N-use efficiency is illustrated by examples from experiments at Rothamsted and Woburn. Between 1968 and 1973, four amounts of N were tested on potatoes, sugar beet, spring barley and spring wheat grown on the silty clay loam on Barnfield at Rothamsted where soils with different amounts of SOM resulted from applying either fertilisers or FYM from 1843.

Table 11: *Mean yields of four arable crops on soils with two levels of soil organic matter and given four amounts of nitrogen, Barnfield, Rothamsted, 1968-73 (adapted from Johnston and Mattingly, 1976).*

Crop	% SOM	Fertiliser N applied, kg/ha			
		0	72	144	216
Potatoes	4.32	24.2	38.4	44	44
tubers, t/ha	1.73	11.6	21.5	29.9	36.2
Sugar beet	4.32	27.4	43.5	48.6	49.6
roots, t/ha	1.73	15.8	27.0	39.0	45.6
		Fertiliser N applied, kg/ha			
		0	48	96	144
Spring barley	4.32	4.18	5.40	5.16	5.08
grain, t/ha	1.73	1.85	3.74	4.83	4.92
Spring wheat	4.32	2.44	3.73	3.92	3.79
grain, t/ha	1.73	1.46	2.97	3.53	4.12

Irrespective of the amount of N applied, yields of the root crops and spring barley, but not spring wheat, were always larger on soils with more SOM, i.e. the applied N was used more efficiently. More importantly for spring barley grown on the soil with 4.3% SOM, maximum grain yield was achieved with 48 kg N/ha rather than 96 kg N/ha required for almost maximum yield (Table 11).

In an experiment on the sandy loam soil at Woburn three amounts of SOM had been established by applying peat for a number of years. Between 1973 and 1980, potatoes, spring barley, winter wheat and winter barley were grown and four amounts of N were tested. For the spring-sown crops, maximum yield was reached with the largest amount of N and yields were always larger on soil with most SOM (Table 12). Yields of the two autumn sown crops were independent of the level of SOM. This suggests that the benefit of extra SOM to soil structure and thus to greater N-use efficiency are more likely for spring sown crops that must develop a root system rapidly to quickly acquire the amounts of nutrients needed to achieve good yields.

Table 12: *Mean yields of four arable crops on soils with two levels of soil organic matter (SOM) and given four amounts of N, Woburn, 1973-80. (adapted from Johnston and Brookes, 1979, Johnston and Poulton, 1980).*

	SOM	Fertiliser N applied, kg/ha[a]			
	%	N0	N1	N2	N3
Potatoes, tubers, t/ha, 1973 &1975	1.31	25.7	35.6	41.7	43.2
	3.51	27.1	40.6	50.7	59.0
Spring barley, grain, t/ha, 1978	1.31	2.19	5.00	6.73	7.05
	3.37	2.58	5.12	6.85	7.81
Winter wheat, grain, t/ha, 1979	1.31	3.54	7.32	8.05	7.82
	3.37	4.81	7.21	8.09	8.08
Winter barley, grain, t/ha, 1980	1.31	3.05	6.01	7.32	7.83
	3.37	3.57	5.92	7.00	7.98

[a] N0, N1, N2, N3: 0, 100, 200, 300 kg N/ha for potatoes
0, 50, 100, 150 kg N/ha for cereals

The importance of SOM in improving N-use efficiency becomes more important as the yield potential of crops improves. This is well illustrated by the data in Figure 8, overleaf. In the Hoosfield Barley experiment two levels of SOM have been produced by applying either PK fertilisers or FYM since 1852 and on each plot four rates of N have been tested since 1968. As the yield potential of the spring barley cultivars has improved, grain yields with each of the four amounts of N have not increased on the soil with only 1.94% SOM. However, yields have gradually increased with change of cultivar when grown on soil with 4.88% N (Figure 8).

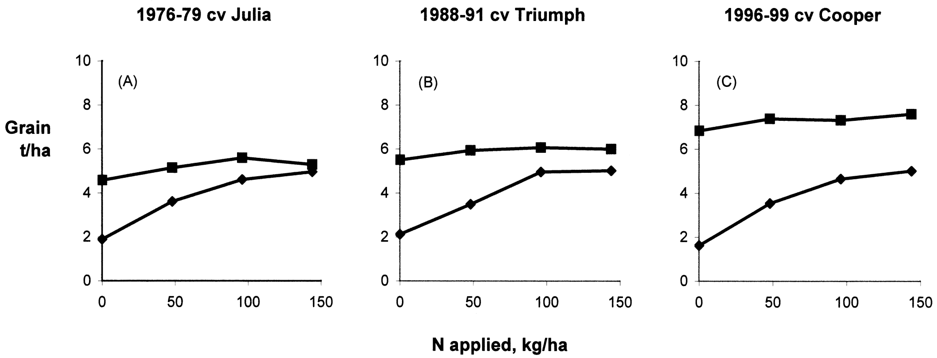

Figure 8: *Yield of spring barley grown on soils with different concentrations of soil organic matter: ♦, 1.94% SOM; ■, 4.88% SOM.*

An interesting facet of N-use efficiency is seen on the Barnfield experiment at Rothamsted. Fertilisers and FYM had been applied to different plots, mostly growing root crops, since1843. In 1958, there was about 2.5 times more SOM in the top 23 cm of the FYM- than in PK-treated soil. In 1975, most of the experiment was sown grass to measure the effects of the accumulated reserves of P and K with a test of 75, 100, 125 and 150 kg N/ha (N1, N2, N3, N4) applied for each harvest (cut) of grass. It came as a considerable surprise when the best yields were on FYM-treated soil and N appeared to be used inefficiently on PK-treated soils. Mean annual grass dry matter yields in the first nine years were 1.5, 1.2, 1.0 and 1.0 t/ha larger with N1, N2, N3 and N4 on the FYM- than on the PK-treated soil. The reason for the difference in yields became clear in 1988 when the soils (0-23cm) were analysed for total N and the values compared with those in 1958 when arable crops were still grown. While %N was largely unchanged in FYM-treated soil, that in PK-treated plots had increased by nearly 20% in the 14 years of continuous grass. In the FYM-treated soil, %N was already at its equilibrium value for the cropping system and N input. In the PK-treated soil, %N in 1958 was at an equilibrium value for continuous arable cropping when the permanent grass was established in 1975. Consequently, SOM and %N in soil began to increase towards a new equilibrium value for grassland and some of the applied fertiliser N was retained in soil rather than increasing grass yields.

7.3. Availability of soil phosphorus.

There are few experiments in which crop response to different amounts of N has been measured on soils with a range of Olsen P levels. Where this could be tested at Rothamsted and Saxmundham there was a strong interaction between N applied and Olsen P in soil. In 1976 in the Exhaustion Land experiment, the range of Olsen P values was limited, 1.6 to 10.1 mg/kg. However, 0, 48, 96 and 144 kg N/ha was tested from 1976 to 1985 on spring barley grown continuously. In Figure 9a Olsen P is divided into three bands, P Index 0- (1.6 to 2.7 mg/kg), P Index 0+ (6.1-7.4 mg/kg) and P Index 1 (10.1 mg/kg). For each amount of applied N, yield was always larger on soil with

most Olsen P but in no case could it be justified to apply more than 96 kg N/ha; to apply more was to use it inefficiently. On the Saxmundham RII experiment there was a wider range of Olsen P levels when spring barley was grown following winter wheat in 1978-79 and 30, 60, 90 and 120 kg N/ha was tested. Soils were divided according to the current P Index system: P Index 0, 0-9 mg/kg; Index 1, 9.1-15 mg-kg; Index 2, 15.1-25 mg/kg and Index 3, 25.1-45 mg/kg, to present the data in Figure 9b. There was no soil at P Index 1 on which 90 kg N/ha was tested. With each amount of applied N yield increased up to P Index 2 and it was not justified to apply more than 90 kg N/ha on P Index 2 soil. There was a small increase in yield with 120 kg N/ha between P Index 2 and 3 soil but more work would be needed to justify recommending that this type of soil should be increased to P Index 3 for spring barley.

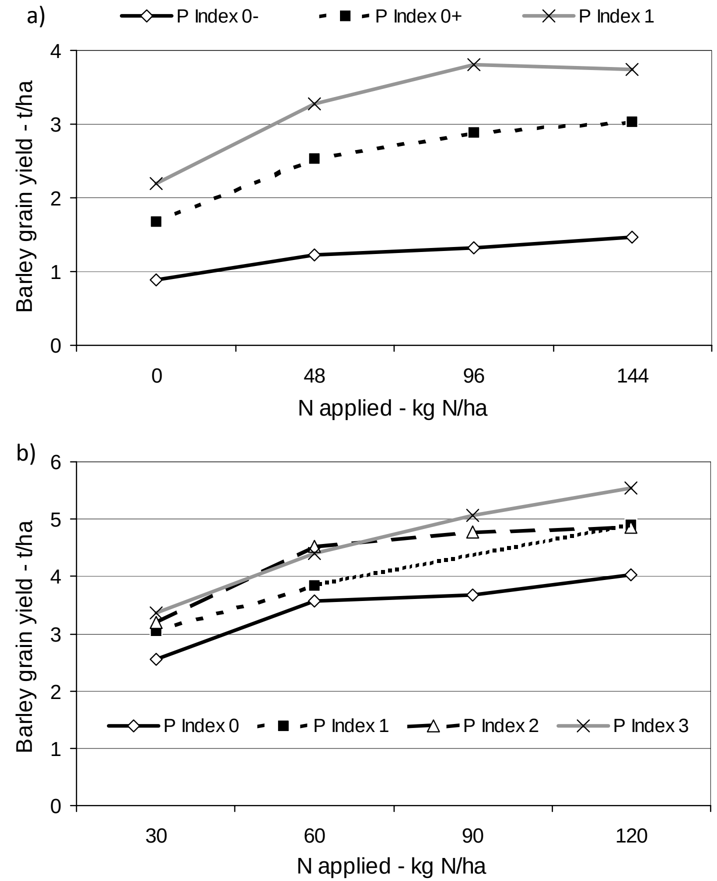

Figure 9: *Yield of spring barley grown on soil with a range of Olsen P levels and given different amounts of fertiliser nitrogen.*
a. Exhaustion Land, Rothamsted, 1976-85.
b. Rotation II, Saxmundham, 1978-79.

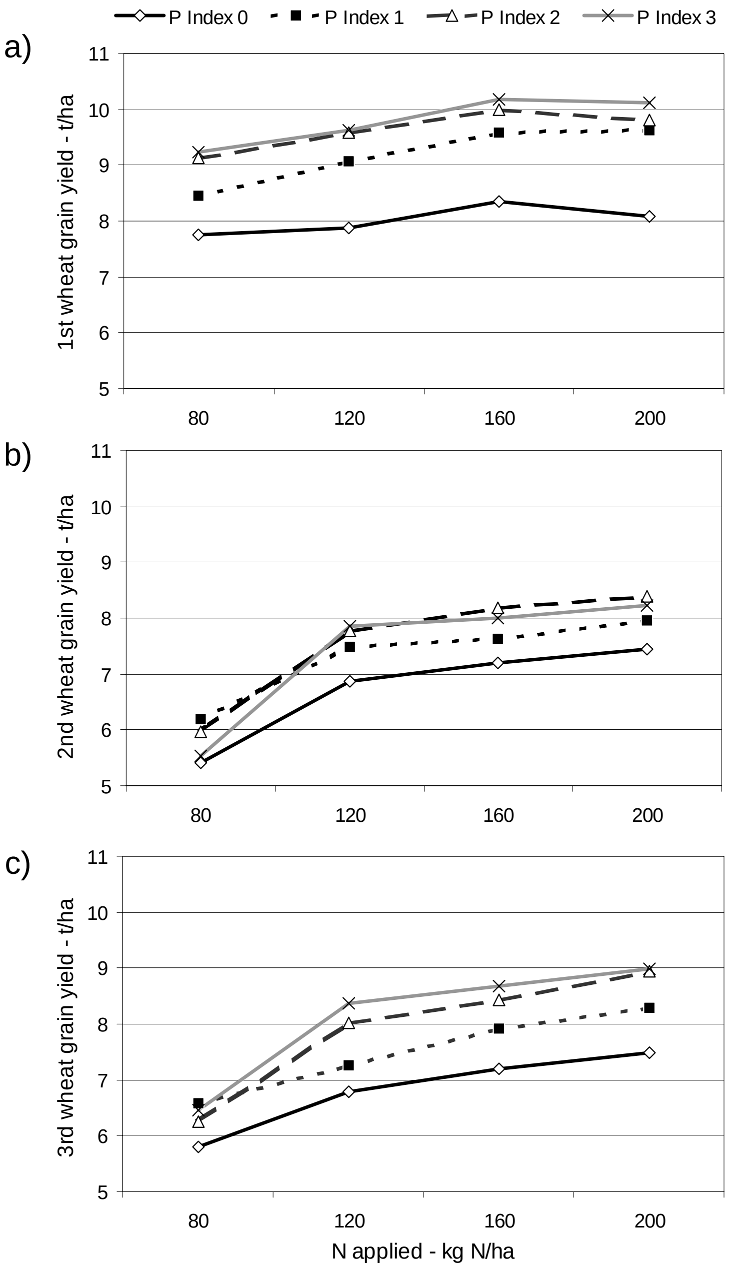

Figure 10: *Yield of winter wheat grown on soil with a range of Olsen P levels and given different amounts of fertiliser nitrogen. 1st wheat after winter beans, 1981-82 followed by a 2nd and 3rd wheat crop in subsequent years, Rotation II, Saxmundham.*

In the Rotation II experiment at Saxmundham, 1st, 2nd and 3rd wheat crops were grown in succession between 1981 and 1984. Four amounts of N were tested, 80, 120, 160 and 200 kg/ha, and grain yields were related to Olsen P (Figure 10) arranged according to the current P Index system. Largest yields of the 1st wheat (Figure 10a) was just over 10 t/ha and were about 2 t/ha less for the second wheat (Figure 10b), possibly because of the effect of take all. Largest yields of the third wheat (Figure 10c) were slightly better than those of the 2nd wheat probably because the adverse effects of take all were beginning to decline. At each amount of N, grain yield increased up to P Index 2 and there was no justification for maintaining soils at P Index 3. For the 1st wheat crop after field beans, 160 kg N/ha gave maximum yield, and it was not justified to apply 200 kg N/ha. Maximum yield of the 2nd and 3rd wheat crops required 200 kg N/ha.

The importance of soil structure, which can be influenced by SOM, in the ability of roots to explore the soil to find nutrients is discussed above. The interaction between SOM, applied N and Olsen P in soil has been measured using spring barley as a test crop in the Agdell experiment at Rothamsted. Soils with two levels of SOM and a range of Olsen P, 3-70 mg/kg, were established over a 12-year period. In 1973-74, spring barley given either 63 or 92 kg N/ha was grown. Grain yields (Table 13) ranged between 4.4 and 6.2 t/ha. On soil with 1.5% SOM, maximum yield with both amounts of N was on soil with 35 mg/kg Olsen P but only 20 mg/kg Olsen P was needed on soil with 2.4% SOM. On soil with only 1.5% SOM the increase in grain yield from the extra 30 kg N/ha ranged from 0.54 to 0.88 t/ha at all four levels of Olsen (Table 13). On soil with 2.4% SOM it was only at the two lowest levels of Olsen P that there was a small positive increase in grain yield from applying the extra N. Thus on soil with more SOM less N was required to achieve maximum yield, i.e. the N was used efficiently.

Table 13: *Effect of increasing levels of Olsen P and two amounts of nitrogen on yields of spring barley grown on two soils with different amounts of soil organic matter, Agdell Rothamsted, mean 1973-1974.*

Olsen P	**N applied, kg/ha**				**Increase in grain yield due to extra 30 kg N/ha**	
	63		92			
	Soil organic matter, %				Soil organic matter %	
	1.5	2.4	1.5	2.4	1.5	2.4
mg/kg	Grain, t/ha				Grain, t/ha	
6	-	4.40	-	4.73	-	0.33
12	4.92	5.64	5.61	5.84	0.69	0.20
20	4.79	6.09	5.67	5.97	0.88	-0.12
35	5.26	6.08	5.80	6.02	0.54	-0.06
54	5.26	6.14	6.04	5.84	0.78	-0.30

7.3. Availability of soil potassium.

Applying N to meet increasing demand by a rapidly growing crop invariable results in a very obvious and frequently expected visual response, which is usually associated with an increase in yield. What is less obvious and rarely realised, however, is that the increased supply of N also increases the amount of water in the crop. As noted earlier, this is because the availability of N increases both cell number and cell size and up to 80-90% of the cell volume is filled with an aqueous solution. The shoots of a cereal crop well supplied with N can contain 10-15 t/ha more water than in a crop with less N. The difference in water content of a sugar beet crop well- and poorly supplied with N can be 30-35 t/ha. The increased water content leads to an increased demand for larger amounts of osmotic solutes, principally as potassium, to maintain turgor. Thus applying more N to increase yield requires more plant-available K in soil and without this K, the response to N will be limited.

This very important interaction between N and K is illustrated by a number of examples given by Johnston and Milford (2008) and Milford and Johnston (2007). Two plots on the sandy clay loam soil at Saxmundham had different levels of exchangeable K (K_{ex}), a measure of plant available K in soil. Winter wheat given four amounts of spring-applied N (together with 40 kg /ha in autumn on all plots) was grown in 1983 and 1984. Although the average increase in grain yield was not large (Table 14) with increasing amounts of N, yield was always larger at each amount of N on soil with more K_{ex}. More importantly, on the soil with more K_{ex} only 160 kg N/ha was needed to get maximum yield, while 240 kg/ha was needed on soil with less K_{ex}. Increasing the amount of N increased grain %N but not to achieve 2.28% N in dry matter.

Table 14: *Effect of soil potassium and applied nitrogen on the yield and grain %N of winter wheat grain grown on a sandy clay loam at Saxmundham, mean 1983-84.*

Soil K status	Nitrogen applied in spring, kg/ha			
K_{ex}, mg/kg	120	160	200	240
	Yield of grain, t/ha			
106	9.66	9.23	9.29	10.33
133	10.80	11.03	10.99	10.94
	Grain %N			
106	1.78	1.94	2.00	2.03
133	1.83	1.96	2.10	2.08

Rothamsted has two unique sets of K-reference plots with K_{ex} concentrations ranging from 40 to 550 mg/kg. Sugar beet and winter wheat were grown on these plots, both with and without an application of 100 kg K_2O/ha (Johnston and Milford, 2008). For the high-yielding cultivar Xi-19, 350 kg N/ha was applied but in two ways; a standard approach (two large applications early in the growing season) and a canopy-managed approach (several smaller applications applied over a longer period of the growing season). The yields, at K Indices 0, 1 and 2-, are in Table 15. Grain yields on K Index 2- soils were just about 11 t/ha irrespective of how the N was applied. Yields on K Index 1 soils were only a little less but the way in which the N was applied began to affect yield, which was smaller when N was applied in only two applications. This effect was more pronounced on K Index 0 soils. On K Index 0 and 1 soils insufficient available soil K was taken up by the crop to allow it to fully utilise the N when it was applied in two large applications early in the growing season, i.e. the N was used inefficiently. Where fresh K was not applied and the canopy approach to N management was used, yield was about 1 t/ha less at K Index 0 compared to 4.2 t/ha less using the standard approach to N management. Applying fresh K did not increase grain yield except on soil at K Index 0 and a little at Index 1 when N was applied in two large amounts early in the growing season rather than in several smaller applications. In general, lower yields on soils at K Index 0 and 1 mean that more of the applied N was unaccounted for and this represents a financial loss to the farmer and a possible environmental cost.

Table 15: *Yields of winter wheat grain and sugar from sugar beet grown on soils at different K Indices and effect of freshly applied potash and different nitrogen treatments, Rothamsted.*

Soil K		Winter wheat, 2 N systems				Sugar beet, 2 nitrogen rates			
		Standard management		Canopy management		90 kg N/ha		150 kg N/ha	
		Fresh K_2O, kg/ha				Fresh K_2O, kg/ha			
Index	mg K/litre	0	100	0	100	0	100	0	100
		Grain, t/ha		Grain, t/ha		Sugar, t/ha		Sugar, t/ha	
2-	121-180	11.0	11.0	10.9	10.9	9.8	9.8	10.3	10
1	61-120	10.1	11	10.7	10.7	9.4	9.0	9.6	8.7
0	0-60	6.8	9.6	9.8	9.9	8.2	8.8	7.8	8.5

For sugar beet, N was tested at 90 and 150 kg/ha with and without a seedbed application of 100 kg K_2O/ha. When no fresh K was applied, average maximum sugar yield was 10.3 t/ha on K Index 2- soils with 150 kg N/ha and decreasing the applied N to 90 kg/ha decreased yield by about 0.5 t/ha (Table 15). Sugar yields were less on K Index 0 and 1 soils by about 0.4 and 1.6 t/ha, respectively, with 90 kg N/ha and somewhat larger, 0.7 and 2.5 t/ha, respectively, with 150 kg N/ha. Sugar yields on K Index 0 and 1 soils were not increased to those on K Index 2- soils by applying fresh K to the seedbed at either amount of applied N. This again shows the importance of maintaining soils at target K Index 2- for all crops in the rotation to maximise the efficient use of applied N.

8. CONCLUDING REMARKS.

The use of fertiliser N is a highly emotive subject, in part because N is considered to be used inefficiently in agriculture, especially arable crop production, and in part because loss of various forms of N from agricultural soils can have adverse environmental impact. However, current food security has been achieved largely through the use of fertilisers, including N, worldwide. The yield potential of most crops has been greatly improved and the introduction of agrochemicals to control weeds, pests and diseases has enabled their yield potential to be realised when sufficient nutrients and water are available. Nitrogen is the nutrient that usually has to be applied to arable crops each year and it invariably gives the largest visual yield response. As the amount of fertiliser N applied increases there are few, if any, exceptions to the observation that there is a curvilinear relation between applied N and yield. Consequently, there is an economic optimum to the amount of N to apply, which varies according to the cost of the fertiliser and the value of the crop produced, both of which can change rapidly. Nitrogen fertilisers should always be used to achieve the maximum economic yield.

The perceived inefficiency of N use in agriculture arises because very often only the percent recovery of N in the saleable product is considered. The plant though takes up N to produce a root system to take up nutrients and water, and an above ground canopy to produce sugars which are transported to the storage organ – the saleable product – where the sugars are converted usually to starch. In terms of the total N in a crop at harvest, ^{15}N-labelled fertiliser experiments suggest that percent N recovery in the above ground crop can be large, up to 80%, but is more frequently in the range 50-70%; this can hardly be considered an inefficient use of the fertiliser N. Where issues can arise is the fate of the N in those parts of the crop which are not sold but which have existed to produce the saleable product. Growing plants also have to compete with the soil fauna, mainly microorganisms, for N and this should be remembered when making judgements about N-use efficiency; it is most unlikely that percent recovery of fertiliser N in field-grown crops will ever approach 100%. Labelled-N experiments allow the fate of much of the applied N to be accounted for in the above ground crop and the soil. However, in such experiments a proportion of the applied N remains unaccounted for. It is the fate of this N that research should aim to understand and seek to minimise.

The most widely used method of assessing N-use efficiency is the difference method, i.e. the difference in the N content of a crop with and without added N divided by the amount of N applied and expressed as a percentage. With this method, N-use efficiency depends on the yield of crops grown with and without N and yield can be affected by weather as well as by weeds, pests and diseases, so N-use efficiency can vary greatly. Also N-use efficiency estimated in this way depends on the amount of N available to the crop in the soil to which no N is applied and this too can vary depending on the management, including fertiliser application, of previous crops. Large amounts of plant-available N in soil usually means that less fertiliser N has to be applied to

achieve optimum yields but not always that the applied fertiliser N is used less efficiently in terms of kg product produced per kg N applied.

Nitrogen use efficiency can be improved by having all those factors that affect the growth of a crop, and thus yield, as near optimum as possible. Many of these factors increase in importance as the yield potential of a crop increases. Applications of fertiliser N should seek to ensure that plant-available N in soil can match the N demand of a crop throughout growth allowing for any N that is already in the soil or may become available during growth. Many of the factors that control growth are amenable to treatment by the farmer and grower. The judicious use of agrochemicals can control weeds, pests and diseases that otherwise can seriously decrease yields. Ensuring optimum soil conditions is vitally important. Principal among these is the amount of plant-available P and K in the soil. These should be maintained near the target index for all crops grown in a rotation. Soil conditions favourable for roots to explore the soil for nutrients and water can be improved by appropriate and timely soil cultivation and while amounts of soil organic matter cannot be readily increased, care should be taken to maintain and if possible increase levels in soil.

APPENDIX TABLES.

Appendix Tables A to F are shown overleaf.

Appendix A: *Grain yields, percent N in grain (gr), N in grain plus straw m(gr+st), kg grain per kg N applied and kg grain increase per kg increase in N in grain plus straw for winter wheat in three periods, Broadbalk, Rothamsted.*

N applied	1st wheat after a 2-year break					Continuous wheat				
kg N/ha	Grain yield t/ha	Grain % N in DM %	N in gr+st kg N/ha	kg gr/kg N applied	kg gr increase/kg increase in N in gr+st	Grain yield t/ha	Grain % N in DM %	N in gr+st kg N/ha	kg gr/kg N applied	kg gr increase/kg increase in N in gr+st
cv. Brimstone, 1985-1990.										
0	2.59	1.50	37	-	-	1.30	1.47	19	-	-
48	5.46	1.46	74	114	78	3.16	1.58	50	66	60
96	7.48	1.67	118	78	60	5.26	1.80	90	55	56
144	8.41	1.95	158	58	48	5.95	1.97	109	41	52
192	8.53	2.09	173	44	44	6.10	2.12	128	32	44
240	8.35	2.16	184	35	39	6.77	2.29	155	28	40
288	8.61	2.22	201	30	37	6.50	2.35	156	23	38
cv. Apollo, 1991-1995.										
0	1.62	1.50	22	-	-	1.26	1.55	18	-	-
48	4.96	1.41	66	103	76	3.42	1.54	50	71	68
96	7.15	1.75	120	75	56	5.43	1.74	89	57	59
144	8.48	1.83	149	59	54	6.54	1.99	124	45	50
192	8.52	2.10	174	44	45	6.56	2.21	139	34	44
240	8.31	2.26	188	35	40	7.52	2.3	172	31	41
288	8.30	2.30	194	29	39	7.52	2.34	176	26	40
cv. Hereward, 1996-2000.										
0	2.07	1.47	28	-	-	1.28	1.47	18	-	-
48	4.81	1.38	63	100	78	3.18	1.48	45	66	70
96	7.11	1.53	104	74	66	5.28	1.67	85	55	60
144	8.53	1.73	144	59	56	6.10	1.85	109	42	53
192	9.25	1.93	173	48	49	7.16	2.14	148	37	45
240	9.27	2.13	196	39	43	7.62	2.34	176	32	40
288	9.11	2.31	211	32	38	8.00	2.42	195	28	38

Appendix B: *Grain yield, percent N in grain, N in grain, kg grain per kg N applied and kg grain increase per kg increase in N in grain for 1st, 2nd and 3rd winter wheat crops, Saxmundham, Suffolk, UK.*

	N applied, kg N/ha								
	200			260			320		
Treatment	no PK	PK	P	no PK	PK	P	no PK	PK	P
1st wheat after beans, 2004-2006.									
Grain, t/ha	10.04	11.58	11.40	10.10	11.65	11.68	10.94	12.08	11.86
% N in grain dry matter	1.98	1.85	1.88	2.10	2.07	2.10	2.23	2.25	2.17
N in grain, kg N/ha	168	182	182	180	205	209	207	232	220
kg gr/ kg N applied	50	58	57	39	45	45	34	38	37
kg gr increase per kg N increase in N in grain	-	110	97	-	62	54	-	46	71
2nd wheat, 2004-2006.									
Grain, t/ha	6.31	8.64	9.00	7.40	9.56	10.75	4.50	9.54	9.06
% N in grain dry matter	2.00	1.91	1.87	2.15	2.09	2.06	2.31	2.40	2.40
N in grain, kg N/ha	105	139	143	134	169	188	88	197	184
kg gr/ kg N applied	31	43	45	28	37	41	14	30	28
kg gr increase per kg N increase in N in grain	-	68	71	-	62	62	-	46	48
3rd wheat, 2005-2006.									
Grain, t/ha	6.76	9.64	9.01	7.14	10.04	9.52	7.56	10.66	9.18
% N in grain dry matter	2.06	1.98	2.05	2.09	2.19	2.10	2.16	2.22	2.19
N in grain, kg N/ha	118	162	158	127	187	170	142	201	172
kg gr/ kg N applied	34	48	45	27	39	37	24	33	29
kg gr increase per kg N increase in N in grain	-	65	56	-	48	55	-	52	54

Appendix C: *Grain yield, % N in grain, N in grain, kg grain per kg N applied and kg grain increase per kg N increase in N in grain for winter wheat and spring barley grown in three rotations[a], Ley-arable experiment, Woburn UK.*

	Winter wheat, 1981-2000				Spring barley, 1982-1991			
N applied, kg N/ha**:**	0	70	140	210	0	60	120	180
Arable cropping[b].								
Grain, t/ha	2.81	5.83	6.73	7.06	2.29	4.56	5.41	5.14
% N in grain dry matter	1.68	1.73	2.06	2.30	1.64	1.65	1.89	2.08
N in grain, kg N/ha	40	85	118	138	32	64	87	91
kg gr/kg N applied	-	83	48	34	-	76	45	28
kg gr increase per kg N increase in N in grain	-	67	50	43	-	71	57	48
Grass ley with N and arable[c].								
Grain, t/ha	3.78	6.55	7.43	7.62	4.15	5.69	5.93	5.59
% N in grain dry matter	1.74	1.81	2.12	2.30	1.62	1.76	1.98	2.15
N in grain, kg N/ha	56	101	134	149	57	85	100	102
kg gr/kg N applied	-	94	53	36	-	95	49	31
kg gr increase per kg N increase in N in grain	-	62	47	41		55	41	32
Grass-clover ley with arable[d].								
Grain, t/ha	5.26	7.55	8.02	7.88	4.16	5.64	5.85	5.39
% N in grain dry matter	1.75	1.92	2.18	2.36	1.70	1.81	2.03	2.16
N in grain, kg N/ha	78	123	149	158	60	87	101	99
kg gr/kg N applied	-	108	57	38	-	94	49	30
kg gr increase per kg N increase in N in grain	-	51	39	33	-	55	41	32

[a] The rotation was three years treatment crops then two test crops, winter wheat and spring barley for which data are given here.
[b] treatment crops: spring barley, spring barley field beans.
[c] a 3-year grass ley given fertiliser N.
[d] a 3-year grass-clover ley.

Appendix D: *Grain yield, percent N in grain, N in grain plus straw, kg grain per kg N applied and kg grain increase per kg increase in N in grain plus straw for spring barley grown continuously, Hoosfield Continuous Barley experiment, Rothamsted, UK. Data for cv. Optic mean 2003-2006.*

	Treatment											
	K only				PK				FYM			
N applied each spring, kg N/ha:	0	48	96	144	0	48	96	144	0	48	96	144
Grain yield, t/ha	0.74	1.16	1.44	1.35	1.95	4.00	5.15	5.68	6.54	7.49	7.93	7.86
% N in grain dry matter	1.55	1.85	2.07	2.17	1.33	1.33	1.44	1.61	1.50	1.65	1.78	1.90
N in grain plus straw, kg N/ha	11	21	30	29	24	51	72	90	92	121	141	150
kg grain per kg N applied	-	24	15	9	-	83	54	39	-	156	83	54
kg grain increase per kg increase in N in gr + st	-	42	37	34	-	76	67	56	-	33	28	23

Appendix E: *Grain yield, percent N in grain, N in grain, kg grain per kg N applied and kg grain increase per kg N increase in grain for winter wheat, 1981-82, and spring barley, 1978-79, Saxmundham Rotation II, Suffolk, UK.*

	Olsen P, mg/kg											
	6				23				36			
N applied each spring, kg N/ha:	80	120	160	200	80	120	160	200	80	120	160	200
Winter wheat.												
Grain yield, t/ha	7.76	7.88	7.59	8.09	8.93	9.44	9.87	9.14	9.21	9.82	10.44	10.48
% N in grain dry matter	1.69	1.82	1.95	2.04	1.66	1.76	1.90	1.96	1.62	1.82	1.92	1.96
N in grain, kg N/ha	111	122	125	140	126	141	158	152	126	152	170	174
kg grain per kg N applied	97	66	47	40	112	79	62	46	115	61	65	52
kg grain increase per kg N increase in N in grain	-	109	-	11	-	34	29	8	-	23	28	26
N applied each spring, kg N/ha:	30	60	90	120	30	60	90	120	30	60	90	120
Spring barley.												
Grain yield, t/ha	2.56	3.13	2.96	3.64	3.18	4.04	4.62	5.10	3.36	4.46	5.18	5.48
% N in grain dry matter	1.45	1.57	1.71	1.85	1.38	1.46	1.52	1.74	1.36	1.37	1.50	1.60
N in grain, kg N/ha	32	42	43	57	37	50	60	75	39	52	66	74
kg grain per kg N applied	85	52	33	30	106	67	51	42	112	74	58	46
kg grain increase per kg N increase in N in grain	-	57	36	43	-	66	63	50	-	85	67	60

Appendix F: *Grain and tuber yield, percent N in grain and tubers, N in grain and tubers, kg grain and tubers per kg N applied and kg grain and tubers increase per kg N increase in grain and tubers, Organic Manuring experiment, Woburn.*

	Treatment											
	Fertilisers				FYM				8-year grass-clover ley			
Winter wheat cv. Mercia, mean 1987-88.												
	N applied in spring, kg N/ha											
	0	50	100	200	0	50	100	200	0	50	100	200
Grain, t/ha	1.66	2.85	4.10	4.02	3.99	5.63	6.46	7.06	4.83	6.76	7.44	7.09
% N in grain dry matter	1.99	2.03	1.97	2.31	1.92	1.75	2.01	2.31	1.88	1.78	2.04	2.24
N in grain, kg N/ha	30	48	68	79	65	84	110	138	77	101	128	135
kg grain per kg N applied	-	57	41	20	-	112	65	35	-	135	74	35
kg grain increase per kg N increase in N in grain	-	66	64	48	-	86	55	42	-	80	51	39
Potatoes cv. Pentland Crown, mean 1988-89.												
	N applied in spring, kg N/ha											
	0	70	140	280	0	70	140	280	0	70	140	280
Tubers, t/ha	24.4	41.4	44.0	45.5	40.3	49.4	54.0	52.7	40.7	52.5	59.4	57.2
% N in tuber dry matter	1.02	1.33	1.54	1.89	1.31	1.42	1.59	1.88	1.04	1.25	1.56	1.80
N in tubers, kg N/ha	53	114	134	167	119	141	172	193	88	139	189	199
kg tubers per kg N applied	-	591	314	162	-	706	386	188	-	750	424	204
kg tuber increase per kg N increase in N in tubers	-	279	242	185	-	413	258	168	-	231	185	149

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