The Rothamsted long-term experiments: Are they still relevant?

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Poulton, P. R. 1996. **The Rothamsted long-term experiments: Are they still relevant?** Can. J. Plant Sci. **76**: 559–571. Maintaining soil fertility and sustaining or increasing crop yield is of worldwide importance. Many factors impact upon the complex biological, chemical and physical processes which govern soil fertility. Changes in fertility caused by acidification, declining levels of organic matter, or P and K status may take many years to appear. These properties can in turn be affected by external influences such as atmospheric pollution, global change, or changes in land management practice. Long-term experiments provide the best practical means of studying changes in soil properties and processes and providing information for farmers, scientists and policy makers. This paper shows how the experiments run at Rothamsted in southeast England continue to provide data which are highly relevant to today's agriculture and wider environmental concerns. Examples are given of how crop yield is affected by soil organic matter, by pests and disease and by P nutrition. The effect of atmospheric pollution on soil acidity and the mobilization of heavy metals are also examined. The need for making better use of existing long-term experiments is stressed.

Key words: Soil fertility, sustainability, long-term experiments, global change

Poulton, P. R. 1996. **Les expériences de longue durée de Rothamsted ont-elles encore une raison d'être?** Can. J. Plant Sci. **76**: 559–571. La conservation de l'acidité du sol ou le maintien et l'accroissement du rendement des cultures sont des sujets d'importance mondiale. De nombreux éléments interviennent dans les processus biologiques, chimiques, et physiques complexes qui gouvernement la fertilité du sol. Les changements apportés par l'acidification, par la baisse des teneurs en matière organique ou par l'évolution de l'état de P et de K dans le sol peuvent prendre de nombreuses années à apparaître. Ces propriétés, à leur tour, peuvent être touchées par des influences extérieures, par exemple la pollution atmosphérique, les changements climatiques à l'échelle planétaire ou les modifications des pratiques de conduite du sol. Les expériences de longue durée constituent le meilleur moyen pratique de suivre les modifications des propriétés et des processus pédologiques et de fournir aux agriculteurs, aux scientifiques et aux décideurs les renseignements dont ils ont besoin. Cette revue montre à quel point les expériences conduites par la station de Rothamsted dans le sud-est de l'Angleterre continuent de fournir des données de la plus haute pertinence pour l'agriculture moderne, de même que pour les préoccupations écologiques qui s'y rattachent. Par des exemples, l'auteur démontre à quel point le rendement des cultures est lié à la teneur en matière organique du sol, à la présence des ravageurs et des maladies et à la nutrition phosphorée. L'effet de la pollution atmosphérique sur l'acidité du sol et sur la mobilisation des métaux lourds est également abordé. L'auteur insiste sur l'importance d'une meilleure utilisation des essais de longue durée existants.

Mots clés: Fertilité du sol, durabilité, expérience de longue durée, modification à l'échelle planétaire

It might be supposed that the field experiments started at Rothamsted in the middle of the 19th century could not possibly be of scientific significance as we approach the 21st. That they are considered not only valuable but, along with other long-term experiments, might even be regarded as essential owes much to the foresight of their originators, J. B. Lawes and J. H. Gilbert, and to succeeding generations of scientists.

Long-term experiments, and the archived material from them, offer the best practical means of understanding many of the problems facing farmers, ecologists and policy makers today. For example, information is needed by governments who are seeking to introduce legislation which limits inputs to the land or the wider environment either by farmers or industry and by scientists trying to assess the effects of global change, often with limited data. Advice is needed by many farmers struggling to support themselves and their families on soils where fertility and yield are declining and where land management may be inappropriate. Factors such as acidification or declining SOM levels which impact upon soil fertility may induce changes which only become apparent over many years; hence the need for long-term experiments. Johnston and Powlson (1994) listed some of the more easily identified objectives for which long-term experiments could be used:

- To test the sustainability of a particular husbandry system over a long time span and determine what changes in husbandry are needed to enhance productivity and maintain sustainability.
- To provide data of immediate value to farmers to improve best husbandry practices.
- To provide a resource of soil and plant material for further scientific research into soil and plant processes which control soil fertility and crop production.
- To allow a realistic assessment of non-agricultural anthropogenic activities on soil fertility and crop quality.

Abbreviations: **FYM**, farmyard manure; **SOM**, soil organic matter

- To provide long-term data sets which can be used to develop or validate mathematical models to predict the likely effects of management practices and of climate change on soil properties, on the productive capacity of soils and on the wider environment.

Implicit in any statement about the value of long-term experiments is the fact that they must be well managed, that any changes have been carefully considered and that they are well documented. Poulton (1996) gives examples of how this can be achieved.

This paper shows how long-term experiments can continue to be of relevance to modern agriculture and to wider environmental issues. The examples are from experiments managed by Rothamsted staff in southeast England. They are at Rothamsted itself on a silty clay loam (Chromic Luvisol) with 700 mm annual rainfall; at Woburn, a sandy loam (Cambic Arenosol) with 600 mm rainfall and at Saxmundham, a sandy clay loam (Eutric Gleysol) with 600 mm rainfall.

EVIDENCE FOR SUSTAINABLE AND NON-SUSTAINABLE PRODUCTION

Perhaps the two best known and most remarkable examples of the continuous and sustained production of arable crops are at Rothamsted. Winter wheat (*Triticum aestivum* L.) has been grown on all, or part of, Broadbalk field each year since 1843 and spring barley (*Hordeum vulgare* L.) has been grown continuously on Hoosfield since 1852. In a third experiment, herbage production has been maintained on permanent grassland (various grass, legume and forb species) on Park Grass since 1856. In this experiment, the principal effect of the treatments, including acidification of the soil from acidifying inputs in rainfall and the use of ammonium sulphate, and the test of liming ($CaCO_3$), has been to greatly modify the species composition and diversity of the sward (Thurston et al. 1976; Tilman et al. 1994).

Yields of both spring barley on Hoosfield and winter wheat on Broadbalk changed little for many decades. Then, with the introduction of modern cultivars with a high yield potential and the use of agrochemical inputs (herbicides, fungicides, pesticides) to protect that potential, yields of both cereals have increased appreciably since the late 1960s. Figure 1 shows the yields of wheat grown on Broadbalk given by FYM, 35 t ha^{-1}, and NPK fertilizers supplying 144 kg N, 33 kg P and 90 kg K ha^{-1} and compares yields with those on the unmanured plot. The unmanured plot yields as much grain now as it did in earlier years. The decline in yields in the 1920s is considered to be because of difficulties in controlling weeds. This was overcome by the introduction of regular fallowing on part of the experiment each year (Poulton 1996). Yields on plots given either 144 kg N ha^{-1} plus PK fertilizers or FYM have remained essentially equal throughout the whole period of the experiment. On soils given only inorganic fertilizers, SOM has remained largely unchanged during the past 100 years. Where FYM has been applied each year, the organic matter content of the soil is now about two-and-a-half times that on fertilizer-only plots (Johnston 1969). The similarity of the yields on these two plots has been used by many to reassure farmers that yields can be maintained by using fertilizers in the absence of organic manures. From the data it was also assumed that the organic matter content of a soil was not very important; recent results suggest that this is not always the case, even at Rothamsted (see later). It is also unfortunate that many have sought to extrapolate this result unthinkingly to other soils and other climates.

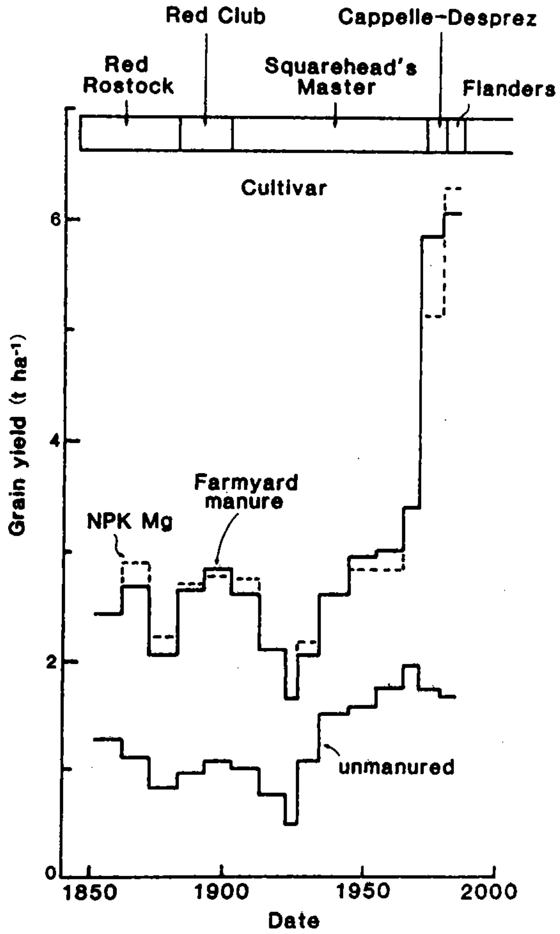

Fig. 1. Broadbalk. Yields of winter wheat, 1852–1986: unmanured; inorganics (144 kg N ha^{-1}, 35 kg P ha^{-1}, 90 kg K ha^{-1} annually); farmyard manure (35 t ha^{-1} annually, containing c. 225 kg N ha^{-1}, 40 kg P ha^{-1}, 210 kg K ha^{-1}) (Jenkinson 1991).

Soil Organic Matter

ORGANIC MATTER CONTENT OF SOIL. In any farming system, SOM content changes towards an equilibrium value that depends on 1) the quantity of added organic material and its rate of decomposition, 2) the rate of breakdown of existing organic matter, 3) soil texture, organic matter is stabilized on clay sized particles, and 4) climate. The effects of these variables on changes in both percent C and percent N in the top 23 cm of soil have been assessed in long-term experiments at Rothamsted and Woburn.

As on Broadbalk the SOM content on Hoosfield has been constant for about 100 yr on both the unmanured plot and

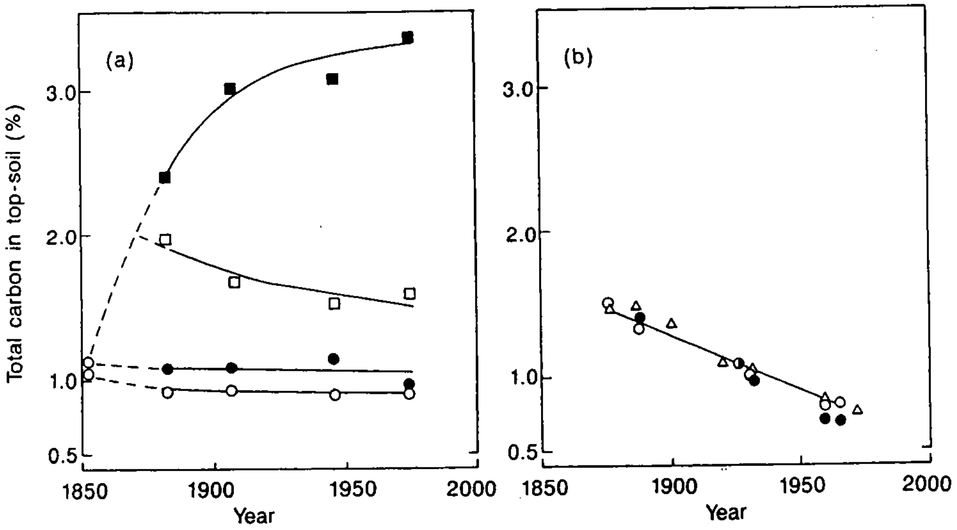

Fig. 2. Total carbon in topsoil, 0–23 cm. (a) Hoosfield, Rothamsted, spring barley each year, annual treatment since 1852, (○) unmanured, (●) PKMg + 48 kg N ha^{-1}, (■) FYM, 35 t ha^{-1}, (□) FYM 35 t ha^{-1}, 1852–1871, none since. (b) Woburn, cereals each year (○) unmanured, (●) NPK, (△) manured four-course rotation (Mattingly et al. 1975; Jenkinson and Johnston 1977).

that given NPK fertilizers (Fig. 2a) (Jenkinson and Johnston 1977). The quantity is a little larger in the fertilized soil because larger crops have been grown and, although straw is removed each year, there have been larger residues from stubble, leaves and roots returned to the soil. Annual additions of 35 t ha^{-1} fresh FYM have increased SOM, rapidly at first and then more slowly as the equilibrium value for this system is approached. It is important to note the time-scale over which this change has occurred, more than 130 yr for this medium-textured soil in a temperate climate.

Figure 2b illustrates the importance of soil texture on equilibrium levels of SOM. The sandy loam at Woburn has about 10% clay compared with 20% clay in the silty clay loam on Hoosfield. At the start of the experiments at the two sites, there was more SOM in soils at Woburn than at Rothamsted [because of a long history of grassland; see Johnston (1991)] but under continuous arable cropping there is now less in Woburn soil (Fig. 2a, b) (Mattingly et al. 1975). Johnston (1991) gave further examples of the slow buildup of SOM under grass and the effects of soil texture in other farming systems at the two sites.

Although in temperate climates the SOM content of soil may change slowly this is not so in the tropics. Jenkinson and Ayanaba (1977) showed that the decomposition of ^{14}C-labelled ryegrass was four times faster under field conditions in the humid tropical climate at IITA (Nigeria) than in the temperate climate at Rothamsted. With hindsight it is unfortunate that the well-founded Rothamsted results on the slow changes in SOM and the lack of crop response to humus level in soil were promulgated so widely *without* the rider that they needed to be confirmed for other soils, under different farming systems in other parts of the world.

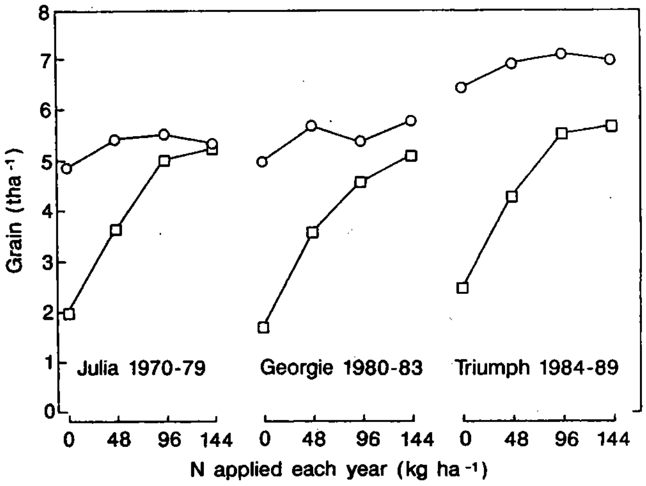

Fig. 3. Hoosfield. Yields of three cultivars of spring barley grown continuously on soils which have received either PK fertilizers (□) or farmyard manure (○) annually since 1852 (Johnston 1991).

EFFECTS OF SOIL ORGANIC MATTER ON YIELD. Figure 3 shows grain yields of three cultivars of spring barley grown on the Hoosfield Continuous Barley experiment since 1970. In this experiment, started in 1852, annual applications of PK fertilizers, 33 kg P, 90 kg K ha^{-1}, and FYM, 35 t ha^{-1} are compared. By 1968 the FYM-treated soils contained two-and-a-half times as much SOM as fertilizer-treated soils, and in that year both plots were divided to test four amounts of N as inorganic fertilizer, 0, 48, 96, 144 kg ha^{-1}. In the first period, 1970–1979, yields of cv. Julia on fertilizer-treated soils given 96 kg N ha^{-1} were the same as on FYM-treated soils. This equivalence of the yields with fertilizers and FYM had been an unchanging feature of the results since the experiment started. In 1980–1983 yields of cv. Georgie on fertilizer-treated soils were again equal to those on FYM-treated soil, but 144 kg N ha^{-1} was needed. More importantly, however, on FYM-treated soils yields were further increased by giving extra fertilizer N. In the third period, 1984–1990, cv. Triumph yielded little more on fertilizer-treated soils than cv. Georgie in the previous period, but much more on FYM-treated soil. Clearly spring-sown crops, with high yield potential, need to grow quickly to achieve good yields and will benefit from improved soil

Table 1. Yields of winter wheat grain (t ha^{-1}) given by fertilizers, farmyard manure and farmyard manure plus fertilizer N, Broadbalk, Rothamsted

	Cultivar grown			
	Flanders 1979–1984		Brimstone 1985–1990	
Treatment	Continuously	In rotation[x]	Continuously	In rotation[x]
NPK[z]	6.93	8.09	6.69	8.61
FYM	6.40	7.20	6.17	7.89
FYM + N[y]	8.13	8.52	7.92	9.36

[z] On fertilizer-only plots best yields of cv. Flanders were given by 192 kg N ha^{-1} and of cv. Brimstone by 288 kg N ha^{-1}.
[y] FYM plus 96 kg ha^{-1} fertilizer N.
[x] First wheat in rotation; fallow, potatoes, wheat, wheat, wheat.
(Johnston 1994.)

physical conditions which will allow more rapid root growth and exploration of the soil for nutrients and water (Gregory 1988). A similar benefit of having extra organic matter in soil is also seen for autumn-sown winter wheat on Broadbalk (Table 1). In recent years yields have always been largest when extra fertilizer N was given to crops grown on FYM-treated soil. On these plots the readily available N from the annual application of FYM and the nitrate mineralized from the SOM is not sufficient for the yield potential of current cultivars.

EFFECT OF ORGANIC MATTER ON N LOSSES. Although the extra N made available from the SOM on the FYM-treated soils is of benefit in increasing yield, it is also subject to large losses — by leaching, denitrification and ammonia volatilization. Webster and Goulding (1989) found that denitrification on Hoosfield in autumn was much greater on the FYM than the inorganic fertilizer only plot. Figure 4 shows the inorganic N in the profile during the autumn/winter period (Powlson et al. 1989). At all times there was more than twice as much inorganic N in the profile under the organic treated plot than under the inorganically fertilized plot. An improved version of the simulation model for mineralization and leaching described by Addiscott and Whitmore (1987) was used to estimate how much of that N was at risk to loss by leaching during the winter period. The estimates were 124 and 25 kg NO_3-N ha^{-1} on the FYM and inorganic fertilizers only plots, respectively.

Obviously this potential for greater leaching losses from organic manures needs to be taken into account when framing legislation which seeks to limit the amounts and times of application of organic manures and fertilizer N that can be used in areas vulnerable to nitrate pollution. (See also section on "Testing efficient use of nitrogen fertilizers".)

Effect of Take-all on Yield

The reasons why Lawes and Gilbert started their experiments with arable crops grown in monoculture has been discussed elsewhere (Johnston and Powlson 1994). On Broadbalk and Hoosfield sustained production has been spectacularly successful, especially when considered against our present knowledge of fungal pathogens and root diseases which can be very damaging. Such diseases have often caused other farmers to abandon continuous cereals because yields were not sustained.

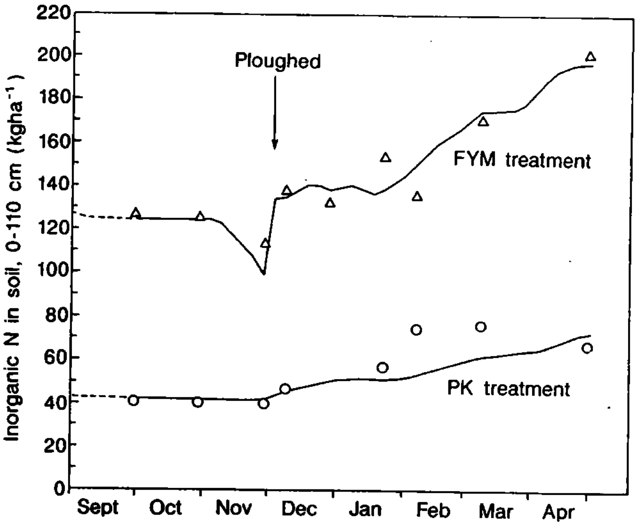

Fig. 4. Hoosfield. Inorganic N (ammonium + nitrate) in soil to a depth of 110 cm in two plots of the Continuous Barley experiment as measured (data points) or simulated (lines). Annual treatment since 1852, PK fertilizers (○), farmyard manure (△). (Powlson et al. 1989.)

Observations of the incidence of take-all, caused by *Gaeumannomyces graminis*, on Broadbalk and other fields gradually led to the idea that when wheat was grown continuously factors inimical to take-all prevented it developing in its most severe form (Glynne et al. 1956); a feature that became known as take-all decline. However, although take-all decline occurred when susceptible cereals were grown continuously, there was evidence to suggest that even with maximum take-all decline, yields could be less than in the absence of take-all. To test this it was decided in 1968 to subdivide each of the five sections on Broadbalk to create 10 sections (Dyke et al. 1983). On some sections wheat was grown continuously, on others after a 2-yr break from cereals, which was known to minimise any risk of take-all affecting the next crop. Break crops have included field beans (*Vicia faba* L.), potatoes (*Solanum tuberosum* L.) and fallow. Yields during the next 15 yr are shown in Fig. 5. From 1970 to 1978, cv. Cappelle Desprez was grown. On plots given fertilizers, yields of wheat grown continuously increased up to 96 kg N ha^{-1} with little further increase to more N; when grown after a 2-yr break, yields peaked at 96 kg N ha^{-1} and then declined. When 96 kg N ha^{-1} was given the benefit of the 2-yr break was 1.8 t ha^{-1} grain. On plots with more organic matter from repeated applications of

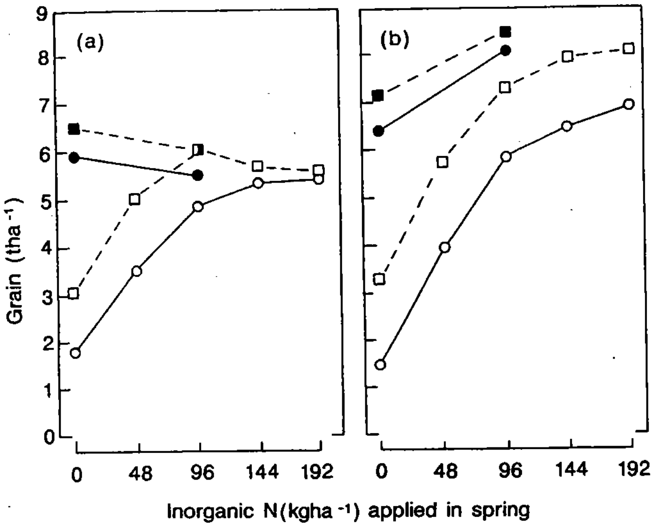

Fig. 5. Broadbalk. Yields of two cultivars of winter wheat, Cappelle Desprez 1969–1978 (Fig. 2a), Flanders 1979–1984 (Fig. 2b), grown continuously or after a 2-yr break on soils which have received either PK fertilisers or FYM annually since 1852: (○) continuous wheat, (□) after 2-yr break; open symbols with PK, closed symbols with FYM. (Jenkinson 1991.)

FYM, the 2-yr break increased yields by only 0.63 t ha^{-1} and yields declined when extra fertilizer N was given. In 1979–1984 cv. Flanders was grown and yields in all situations increased up to the maximum amount of N tested (192 kg ha^{-1}) (Jenkinson 1991). At this level of N the benefit of the 2-yr break was 1.14 t grain ha^{-1} on fertilizer-treated soils; on FYM-treated soils the effect of 96 kg N ha^{-1} was less, only 0.14 t ha^{-1}. The different efficiency with which fertilizer N was used in the two periods was because fungicides were used to control foliar pathogens in the second period, but not in the first. The effect of breaking take-all decline by having a 2-yr break and then three consecutive wheats has been tested since 1985. With inorganic fertilizer, FYM and FYM + N, best yields of the third wheat after a 2-yr break were always less than those of wheat grown continuously (Table 2) because after a 2-yr break from cereals the causative agent for take-all decline built up less quickly than *Gaeumannomyces graminis*.

Thus, in this long-term experiment, continuous wheat production has not only been sustained but increased, the value of extra organic matter in soil has been demonstrated and the role of take-all and take-all decline shown. There is also an important message for farmers, namely that whilst is has been possible to grow wheat continuously on this soil with careful attention to management, there are benefits to be obtained if profitable crop rotations can be devised in which most wheat crops are grown after a 2-yr break.

Use of Nitrogen Fertilizer

FERTILIZER NITROGEN EFFICIENCY. Besides effects on yield, one important observation from changing cultivars on Broadbalk has been the improvement in recovery of fertilizer nitrogen by the grain. This was clearly demonstrated when, for 3 yr in the 1980s, an old long-strawed variety (Squarehead's Master) and a modern short-strawed variety (Brimstone) were grown side-by-side on some treatments. Austin et al. (1993) showed that, as expected, total dry matter production was very similar, but that the modern variety yielded much more grain than the older one because of its higher harvest index. Averaged over all the treatments tested the increase in grain yield was 52% but was proportionately greater at higher rates of fertilizer N (Table 3). The apparent recovery of fertilizer N by the grain was also greater in the modern variety, despite having a lower concentration of N in the grain. The data showed that less land or less fertilizer N is needed to produce 1 tonne of grain with a modern cultivar compared to an older one (Table 3).

TESTING EFFICIENT USE OF NITROGEN FERTILIZERS. Concern over nitrate in potable waters and the environmental effects of nitrate in rivers led to further research into the efficient use of fertilizer N. This could best be done using labelled ^{15}N fertilizer on a site where SOM is in equilibrium, i.e. where the annual production of soil organic N is equal to the amount mineralized each year. Powlson et al. (1986) described experiments made during 4 yr on Broadbalk, in which varying rates of ^{15}N-labelled fertilizers were applied to winter wheat. Averaged over 4 yr c. 20% of the spring applied N fertilizer was found in the soil after harvest (Table 4) but less than 2% of the total applied was present as mineral N, with most being present in organic forms. The N balance for these experiments, using measured values for N in soil, grain and straw (Table 4), showed that, by difference, c. 20% of the applied N was unaccounted for. In these and similar experiments there was a strong relationship between the loss of spring-applied labelled N and rainfall (or soil wetness) in the 3 wk after fertilizer application (Addiscott and Powlson 1992; Powlson et al. 1992). The losses could have been by volatilization, leaching or denitrification. The latter was considered the most likely because, whilst the soils were wet enough for denitrification to occur, rainfall did not exceed evapotranspiration (except for one site in one year) for soils already below field capacity and thus leaching was unlikely to be the dominant loss process. The soil conditions at the sites were not conducive to anaerobic volatilization. The data also indicated (Powlson et al. 1986) that on Broadbalk there is now an annual input of about 50 kg N ha^{-1} from the atmosphere, a figure subsequently confirmed by direct measurement (Goulding 1990). Such inputs need to be identified and allowed for when making fertilizer recommendations.

These results and others (Macdonald et al. 1989) demonstrated that most of the nitrate present in soil in autumn comes from the mineralization of organic matter, at least under the climatic conditions of southeast England and where autumn-sown cereals have been grown. This is an important observation for those framing legislation on N fertilizer use. Exceptions are where N has been applied in excessive amounts relative to the yield potential of the site for a particular crop or where the crop has failed for some reason [see Johnston and Jenkinson (1989) for further examples].

Table 2. Yields of grain (t ha^{-1}) of first, second and third wheat after a 2-yr break compared with wheat grown continuously, Broadbalk, Rothamsted 1985–1990

Treatment	Wheat after a 2-year break 1st	2nd	3rd	Continuous wheat
NPK[z]	8.61	7.85	6.47	6.69
FYM	7.89	5.86	5.37	6.17
FYM + N[y]	9.36	8.64	7.59	7.93

[z] Best yield of cv. Brimstone was given by 288 kg N ha^{-1}.
[y] FYM plus 96 kg ha^{-1} fertilizer N.
(Johnston and Powlson 1994.)

Table 3. Comparison of two wheat varieties grown on Broadbalk, 1988-90

	Fertilizer[z] N (kg ha^{-1}) and cultivar 48		144	
	B[y]	SM[x]	B	SM
Grain yield (t ha^{-1})	3.21	2.26	5.42	3.41
Apparent recovery of fertilizer N (%)	66	59	64	51
Fertilizer N needed to produce 1 t grain (kg)	14.9	21.2	26.6	42.2
Land needed to produce 1 t grain (ha)	0.31	0.44	0.18	0.29

[z] Plots also received 35 kg P ha^{-1} and 90 kg K ha^{-1} annually.
[y] Brimstone.
[x] Squarehead's Master .
[Adapted from Austin et al. (1993).]

Table 4. Percentage distribution at harvest of fertilizer-derived nitrogen applied to winter wheat at 144 kg N ha^{-1} labelled with ^{15}N, Broadbalk, Rothamsted

Year	% fertilizer nitrogen Grain	Straw	Soil	Unaccounted for
1980	55	13	17	15
1981	37	16	20	27
1982	45	23	24	8
1983	44	13	16	27
Mean	45	16	19	19

[Adapted from Powlson et al. (1986).]

The other consideration is that the long-continued use of nitrogen fertilizers can lead to the accumulation of more SOM in fertilized soils compared with those which are unfertilized. For example, on most sections of Broadbalk, straw has always been removed at harvest and the only return of organic matter has been in stubble, roots, root exudates and fallen leaves. Shen et al. (1989) showed that the soil which had received 144 kg ha^{-1} fertilizer N each year since 1852 contained 3600 kg ha^{-1} organic nitrogen in the top 23 cm, compared to 2900 kg ha^{-1} in soil receiving no nitrogen. There is a risk of enhanced loss of nitrate by leaching in winter if the extra SOM is mineralized in autumn when crop demand is small. It is worth noting that even where no fertilizer N has been applied since 1852 the soil profile (0–100 cm) will still contain 30–50 kg ha^{-1} of inorganic N in early autumn (Glendining et al. 1990). Differences in the amount of N mineralized should be used to modify the quantity of fertilizer N applied in spring.

Per unit area of land, these amounts of extra nitrogen from the build up of organic matter from the use of fertilizer are small (Glendining et al. 1990) relative to the much larger quantities of nitrate mineralized in the first autumn or spring following the ploughing of grass-clover leys, the incorporation of residues from grain legumes, or applications of organic manures (discussed earlier). Recent work on grass-clover leys (Johnston et al. 1994) has shown that when leys of differing age are ploughed the amount of N mineralized and made available to the following crop is very variable. This may make subsequent decisions on the amount of fertilizer N needed to maximize yield very difficult and may lead to excessive amounts being applied. Increased yields of wheat from the mineralization of N appeared to last only 1 yr. The following spring-sown crop of potatoes yielded more after longer leys but this benefit was related to effects of organic matter other than N mineralization. There was evidence that large amounts of nitrate were formed during the autumn following ploughing and subsequently leached (Johnston et al. 1994).

Information obtained over many years on the mineralization of N from SOM and the efficiency with which fertilizer N is used is invaluable when considering the environmental aspects of fertilizer N use and devising advice systems that take account of both agricultural and environmental requirements.

Phosphorus and Potassium

Phosphorus and potassium are essential for crop growth and, in ionic form, both are taken up by roots from the soil solution where supply must be capable of meeting demand if crop growth is not to suffer (Wild and Jones 1988). Both ions can be held in soil on sites from which they are readily removed by dilute extractants; e.g. 0.5 M $NaHCO_3$ at pH 8.5 for P, 1 M NH_4OAc for K. The amounts extracted, which include those in the soil solution, are best considered as readily soluble and it is often possible to get a good relationship between crop yield and the concentration of readily soluble P and K. In addition, both nutrients can be held on sites or in forms which are not extracted by these reagents but are nevertheless plant available in the long-term. Currently there is no quick reliable laboratory method to determine this fraction of soil P and K although the quantities may play a very significant part in sustainable land use. Both P and K can also occur in forms which are, at best, only very slowly available to plants. These pools or categories of P and K can be represented diagrammatically as in Fig. 6 which shows that both nutrients can transfer in either direction between the various pools. Data to show that such transfers occur, both for P and K are given in Tables 5 and 6, respectively. When the nutrient balance in any one cropping period is positive, readily soluble and non-soluble residues accumulate whilst, when the balance is negative, residues decrease. (In Table 6 balance is defined as K applied minus that removed in harvested crop.) In cases of both accumulation and depletion the change in the readily soluble pool was only a fraction of the total balance. Long-term balance studies can also be used to indicate whether subsoils are an important source or sink for P or K.

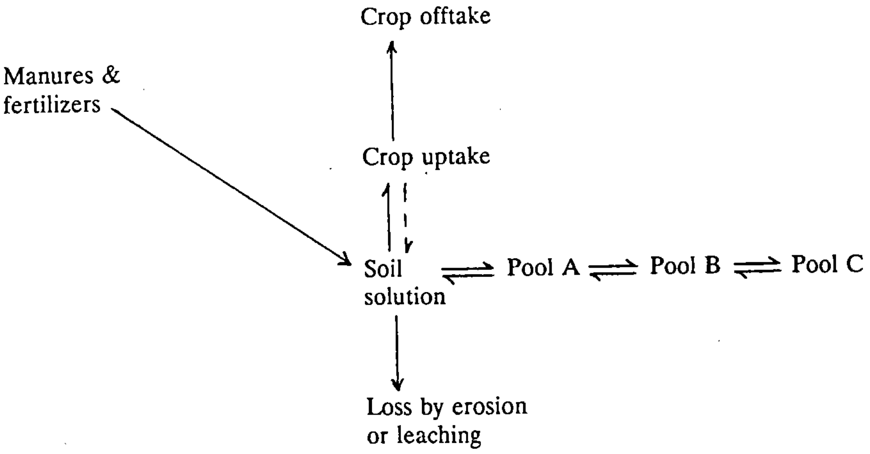

Fig. 6. A simplified P and K cycle for some farmed soils showing transfer of both nutrients between the various pools and the soil solution. Pool A — readily soluble; e.g. P soluble in 0.5 M $NaHCO_3$ at pH 8.5, K exchangeable to 1 M NH_4OAC. Pool B — not readily soluble but plant available in the long-term. Pool C — only very slowly available.

Table 5. Relationship between P balance and decline in $NaHCO_3$-soluble P in a sandy clay loam, Saxmundham 1969–1982 where no fertilizer P was added after 1968

	Main plots[z] with different levels of soluble P in 1969							
	1	2	3	8	4	6	5	7
$NaHCO_3$-soluble P (mg kg^{-1}) 1969	3	7	21	28	39	44	54	67
P removed in crops (kg ha^{-1}) 1969-1982	94	153	217	237	253	256	263	263
Decrease in soluble P (kg ha^{-1}) 1968-1982	8	12	27	50	65	78	87	120
Change in soluble P as a % of crop uptake	8	8	12	21	26	30	33	46

[z]Different combinations of treatment between 1899 and 1968 resulted in eight main plots with different levels of soluble P.
Adapted from Johnston et al. (1985) and Johnston and Poulton (1992).

Table 6. Effect of K balance on exchangeable K in soil in the Garden Clover experiment, Rothamsted, 1956–1983

	Average annual K dressing (kg ha^{-1})	K balance (kg ha^{-1})	Exchangeable K (kg ha^{-1}) during each period			Change in exchangeable K as percentage of K balance
			At start	At end	Difference	
1956–1966	None	–246	171	194	+23	–
	136	+617	171	431	+260	+42
1967	Additional[z]	+432	194	338	+144	+33
1968–1978	250	+1667	375	1065	+690	+41
1979–1983	125	–1494	1065	502	–563	–38

[z]Additional dressing, 437 kg K ha^{-1} applied once only to plot which received no K during 1956–1966.
(McEwen et al. 1984.)

That plant available P and K residues can accumulate in soil is important but economically it is equally valid to ask to what extent should residues be built up in soil. This question is best answered [for reasons see Johnston et al. (1985)] by having plots with a wide range of readily soluble P and K on the same soil type and under the same management. However, it takes a considerable time for both P and K to equilibrate within the various soil pools; experience at Rothamsted suggests up to 12 yr is required. Figures 7a and 7b show the relationship between the yield of potatoes and sugar (from sugar beet, *Beta vulgaris* L.) and readily soluble P on a sandy clay loam at Saxmundham. The twofold difference in yield between groups of years was because of differences in summer rainfall (Johnston et al. 1985). However, the readily soluble P level at which yield approached the asymptote was not appreciably different for the different asymptotic yields. There was therefore a soluble P level which it would not be necessary or economic to exceed. Manuring should seek to maintain the soil just above the critical value for each crop as determined for each soil type. But, in terms of sustainable production it is very important to realise that when soluble P levels decline below the critical value yields begin to fall catastrophically. Allowing levels of available P and K to fall below the critical point, thus restricting yield, would certainly mean that nitrogen, either mineralized from SOM or applied as fertilizer, was used less efficiently. However, in the case of P, greatly exceeding this critical level may lead to an increase in the loss of phosphate

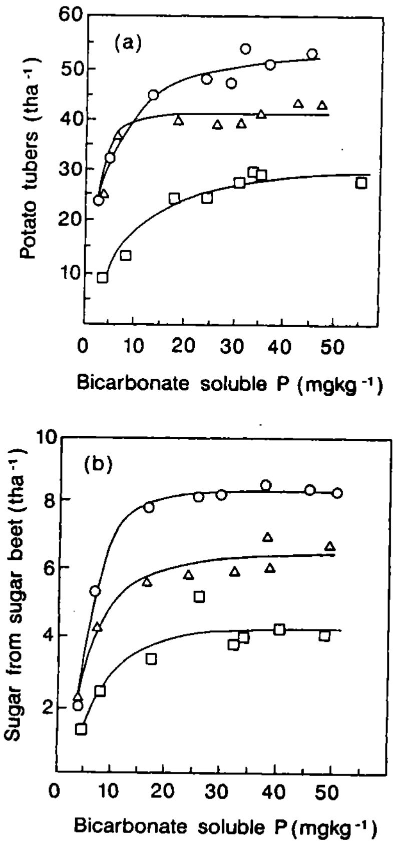

Fig. 7. Relationship between yield and phosphorus soluble in 0.5 M $NaHCO_3$ at Saxmundham. (a) potatoes (□) 1970; (△) 1969, 1972, 1973; (○) 1971, 1974. (b) Sugar from sugar beet (□) 1970, 1974; (△) 1972; (○) 1969, 1971, 1973. (Johnston et al. 1985.)

in drainage water. Although this loss may be small in agronomic terms, the resulting environmental problems caused by phosphate in aquatic ecosystems may be severe (Heckrath 1995).

The data in Fig. 7 were obtained from plots given no P fertilizer after 1968, and where a range of arable crops were grown. The total amount of P removed by the crops and its relation to the decline in soluble P is in Table 5. Soluble P levels in soil were determined every 2 yr (Fig. 8a); the rate of decline in soluble P depended on the initial level. The individual decline curves could be brought into coincidence by suitable horizontal shifts (Johnston et al. 1986a) to indicate the likely rate of decline in soluble P over a 60-yr period (Fig. 8b).

In another experiment the effect of SOM on the crop response to soluble P was investigated. The Agdell experiment, started in 1848, is on one of the more difficult soils at Rothamsted, with approximately 30% clay in the topsoil. The experiment was modified in 1958 with half the plots going into grass and half continuing in arable cropping (Johnston and Penny 1972). Existing plots were divided to build up different levels of soluble P in the soil using superphosphate. At the end of 12 yr there were two groups of soils, with 1.5 and 2.4% organic matter, respectively. Within each “organic matter group” there were 24 subplots with soluble P values ranging from 4 to 70 mg P kg^{-1}. These soils could be divided into five “soluble P groups”. Yields of

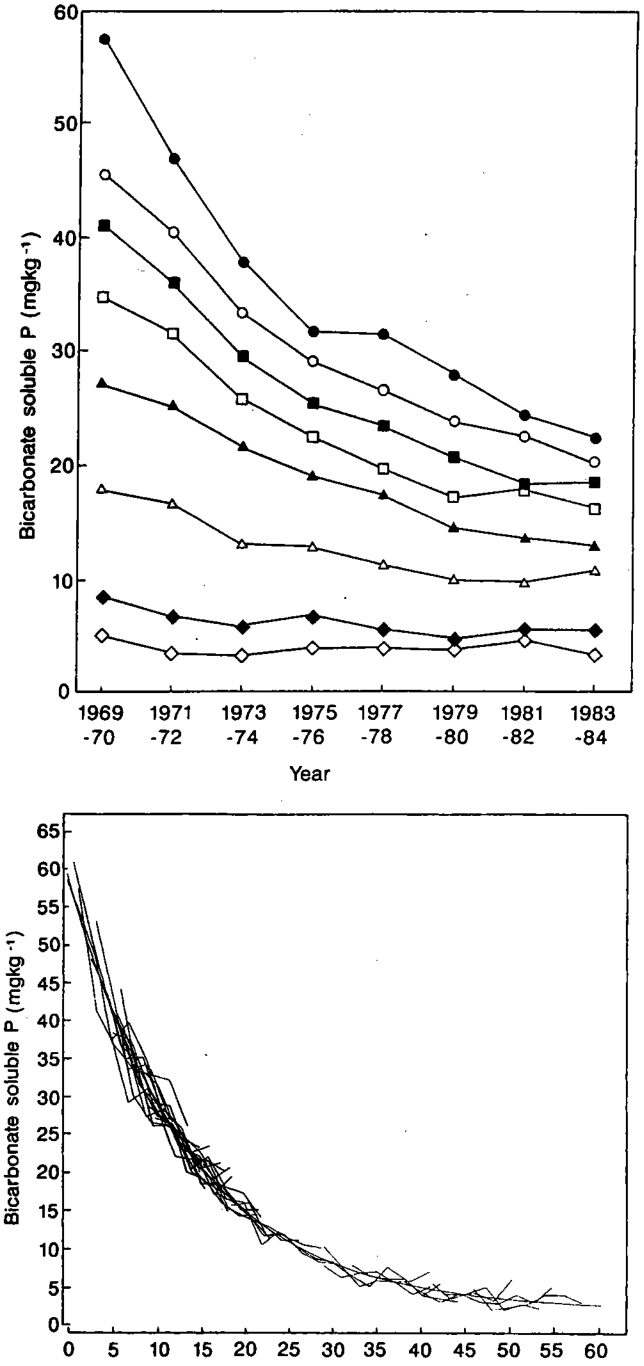

Fig. 8. (a) Shows the change with time in P soluble in 0.5 M $NaHCO_3$ in soils at Saxmundham when no further P was applied after 1968. Symbols indicate soils which contained different amounts of soluble P in 1969–1970 as a result of previous treatment. (b) shows the data for the soils shown in (a) shifted horizontally to bring the curves, for decline in soluble P with time, into coincidence. [Adapted from Johnston et al. (1985) and Johnston and Poulton (1992).]

Table 7. Yields (t ha^{-1}) of potatoes, sugar from sugar beet and spring barley on soils with different amounts of readily soluble P and at two levels of soil organic matter

Crop	% organic matter in soil	P soluble in 0.5 M NaHCO$_3$ (mg kg^{-1}) 0-9	9-15	15-25	25-45	45-70
Barley grain	1.5	—	2.71	3.29	4.21	4.61
	2.4	3.18	4.78	5.20	5.00	5.46
Potato tubers	1.5	—	31.5	36.7	39.3	44.0
	2.4	26.6	43.0	45.3	46.4	47.8
Sugar from sugar beet	1.5	—	5.03	5.91	6.66	6.80
	2.4	2.45	5.92	7.06	6.73	6.85

Johnston and Poulton (1992).

spring barley, potatoes and sugar from sugar beet at each of the five levels of soluble P were always larger on soils with more organic matter (Table 7) (Johnston and Poulton 1992) especially in the groups 9 to 15 and 15 to 25 mg P kg^{-1} which is the range in which many farmed soils in the UK fall (Johnston 1986).

These observations on the inter-relationship between yields, the level of soluble P and the effect of soil texture perhaps help explain why correlations between yield and soil analysis over a range of soils are often poorer than those found within an individual soil type. The effects of SOM may act through effects on anion exchange sites but the results on Agdell strongly suggest that improved soil structure increased the ability of roots to explore the soil for nutrients and this resulted in higher yields on soils with medium levels of soluble P. Long-term sites are essential for conducting studies which probe these complex interactions.

The role of phosphorus in crop production and soil fertility is discussed in more detail by Johnston and Poulton (1992).

Compared to P it has been less easy to determine critical levels of readily soluble K in Rothamsted soils because they contain micaceous clays which release K. Figure 9a shows that for spring barley there was no response to readily soluble soil K above c. 90 mg kg^{-1} exchangeable K whilst potatoes (Fig. 9b) were responding up to 200 mg K kg^{-1}. The scatter in the relationship is probably because the crops obtained variable amounts of K from soil horizons below 23 cm (Johnston and Goulding 1990). Also, potassium in pool B (Fig. 6) may contain K of widely varying availability when soils are stressed to provide K and for some soils it may be many years before the K in pool C becomes the only source of K (Johnston 1988).

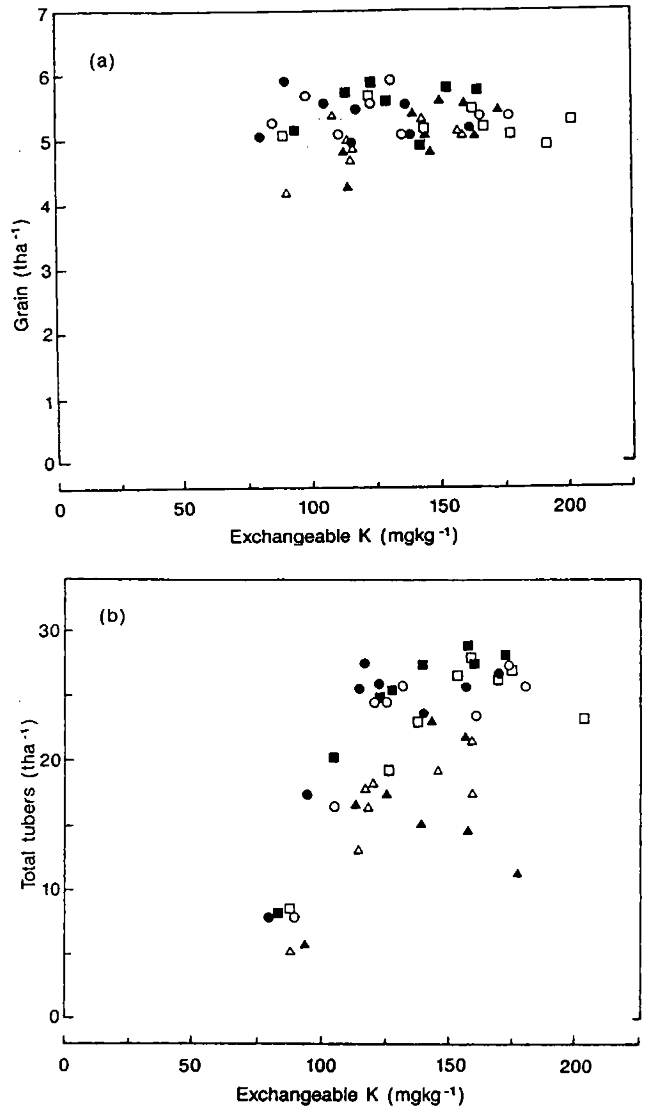

Fig. 9. Relationship between yield of spring barley (a) and potato tubers (b) and K exchangeable to 1 M NH$_4$OAC in Rothamsted soil. Symbols denote different previous cropping and treatment (Johnston and Goulding 1990).

Soil Acidity

Soils are acidified through a number of processes. These include biological activity and other natural processes in soil, atmospheric deposition of acidifying pollutants, additions of fertilizers and, to a lesser extent, crop growth removing calcium (Rowell 1988). Soil acidification is a worldwide problem and can have a major effect on sustainable land use, both through the direct influence on crop

Table 8. Yields of wheat and barley grain (t ha^{-1}) and effect of chalk on plots given ammonium sulphate, Continuous Wheat and Barley experiments, Woburn

Crop and	Period				
Treatment^z	1877–1986	1887–1996	1897–1906	1907–1916	1917–1926
			Winter wheat		
Unmanured	1.08	0.83	0.61	0.66	0.46
NPK					
No chalk	2.04	1.94	1.68	1.11	0.64
Chalk^y	–	–	–	1.25	0.66
FYM	1.76	1.83	1.69	1.38	1.20
			Spring barley		
Unmanured	1.56	0.98	0.60	0.60	0.49
NPK					
No chalk	2.57	2.10	0.19	0.19	0.30
Chalk	–	–	1.39	1.39	0.90
FYM	2.39	2.30	1.87	1.87	1.54

^{z}46 kg N ha^{-1} as ammonium sulphate, FYM 17.6 t ha^{-1} yr^{-1} on average.

^{y}2.5 t CaO ha^{-1} to winter wheat, half in 1905, half in 1918.

10.0 t CaO ha^{-1} to spring barley, half in 1898, half in 1912.

pH, in water, of soils sampled in 1927 were: wheat, no chalk 4.6; chalk 5.0: barley, no chalk 4.8; chalk 5.8. Chalk would have raised soil pH more soon after application.

Adapted from Johnston (1975).

Table 9. Yields (t ha^{-1}) of turnips and winter wheat in the Agdell Rotation experiment, Rothamsted 1848–1951

	Crop and treatment			
	Turnip roots		Wheat grain	
Years	None	NPK	None	(NPK)^z
1848–1851	1.31	2.92	1.91	1.93
1852–1883	0.24	3.47	1.46	1.96
1884–1899	0.13	5.09	1.60	2.47
1900–1919	0.11	3.98	0.97	1.37
1920–1935	0.08	1.61	0.98	0.91
1936–1951	0.04	0.54	1.27	2.07
Soil pH 1953	8.2	5.6		

^{z}NPK fertilizers were applied only once every 4 yr to the turnips. Wheat followed a 1 yr clover ley which would have left a nitrogenous residue.

Adapted from Johnston and Penny (1972).

yields and through the mobilization of heavy metals into soluble forms (Kennedy 1992).

EFFECTS OF SOIL ACIDITY ON CROP YIELD. In marked contrast to the sustainability of cereal yields at Rothamsted, yields of barley, and to some extent wheat, grown continuously on the sandy loam soil at Woburn began to decline about 15 yr after the experiments started in 1876 (Table 8). Lawes and Gilbert were instrumental in starting these experiments in which winter wheat and spring barley were grown each year. The manurial treatments were similar to those on Broadbalk and Hoosfield at Rothamsted and included a comparison of ammonium sulphate and sodium nitrate. The decline in yield was most marked on plots given N as ammonium sulphate and tests of lime ($CaCO_3$) were started in 1898 (Johnston 1975). However, liming did not fully restore yields to those in the early years of the experiment (Table 8). With hindsight there might also have been a buildup of cereal cyst nematode (*Heterodera avenae*) on this light-textured soil because cereal yields also declined on plots getting sodium nitrate, which had little effect on soil pH (Johnston and Chater 1975), and did not decline where cereals were grown in rotation on adjacent experiments.

At Rothamsted, the silty clay loam soil had as much as 5% free calcium carbonate when the experiments started, and the use of ammonium sulphate, supplying up to 144 kg N ha^{-1}, caused no serious problem with soil acidification until the late 1940s. At that time remedial action was taken to adjust soil acidity to near pH 7 and a scheme of regular liming was introduced to prevent further problems developing (Rothamsted Experimental Station 1955). This prevented a serious decline in yields of continuous wheat and barley which would probably have occurred by the 1970s.

Problems did occur, however, on the Four-course Rotation experiment on Agdell field which started in 1848 (Johnston and Penny 1972). Turnips (*Brassica rapa* L.), spring barley, clover (*Trifolium pratense* L.) or beans (*Vica faba*) and winter wheat were grown in rotation. Nitrogen was tested only on the turnips and was applied as a mixture of ammonium sulphate and rape cake. Increasing soil acidity after 80 yr allowed Club root (caused by the fungus *Plasmodiophora brassicae*) to flourish. The fungus spread onto the other plots and so decreased turnip yields (Table 9) that the rotation had to be stopped in 1951. Yields of winter wheat were not affected so seriously (Table 9). Soil pH was raised subsequently by applying lime but, because *Plasmodiophora brassicae* can persist in soil for long periods turnips could not be grown. The experiment was extensively modified in the 1950s.

EFFECT OF VEGETATION ON RATE OF SOIL ACIDIFICATION. One plot of the Park Grass experiment at Rothamsted which started in 1856 has remained unmanured since then. The sward is a mixture of about 40 different grasses, legumes and forbs (Tilman et al. 1994). Initially the 0- to 23-cm depth of soil had a pH in water of about 5.6. Less than 1 km

Table 10. Effect of acidifying inputs from both "natural" sources and fertilizer on soil pH at different depths under woodland and grassland at Rothamsted

	Horizon (cm)	Year and experiment				
		Geescroft Wilderness — Woodland				
		1883	1904	1965	1983	1991
Natural inputs	0–23	7.1	6.1	4.5	4.2	4.3
	23–46	7.1	6.9	5.5	4.6	5.1
	46–69	7.1	7.1	6.2	5.7	6.0
		Park Grass — Grassland				
		1876	1923	1959	1984	1991
Natural inputs	0–23	5.4	5.7	5.2	5.0	4.8
	23–46	6.3	6.2	5.3	5.7	5.4
	46–69	6.5	–	–	–	5.7
Fertilizer input[z]	0–23	4.2	3.8	3.7	3.4	3.2
	23–46	6.3	4.4	4.1	4.0	3.8

[z] 144 kg N ha^{-1} as ammonium sulphate each year since 1856.
(Johnston et al. 1986b).

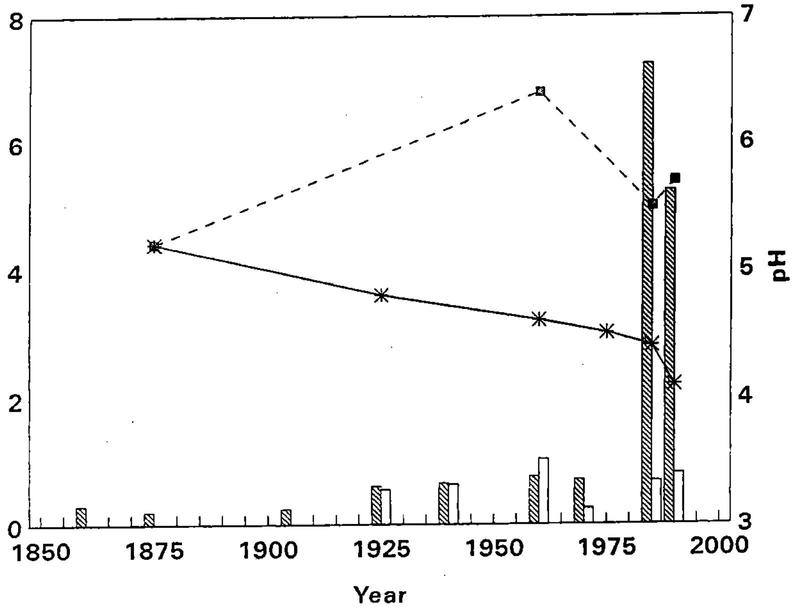

Fig. 10. Park Grass. Aluminium (Al) in hay from unlimed (▨) and limed (☐) sections of plot 3 and its relationship to pH (in $CaCl_2$) in soil from the 0- to 23-cm layer of the unlimed (*) and limed (■) sections (Blake et al. 1994).

away, on the same soil type, is Geescroft Wilderness. This was part of an old arable field until it was fenced off in 1886 when the top 23 cm of soil had a pH about 7.1. Since then the site has been untended and a mature deciduous woodland has developed. Table 10 shows that surface soil pH is now about 4.8 on the Park Grass plot and 4.3 under the Wilderness. Soil acidification, arising at least in part from aerial pollutants, has been quicker and more intense (about 3 pH units in 100 yr) on Geescroft, than on Park Grass (about 1 pH unit in 140 yr). Other causes of soil acidification, at or near neutral pH, are the natural inputs of H^+ from the dissolution of CO_2 and subsequent dissociation of carbonic acid, and the mineralization of organic matter. These processes will become less important as pH falls. The difference between the two sites may be that the tree canopy is more efficient at trapping aerial pollutants than the low growing herbage. Under the trees the 23- to 46-cm and 46- to 63-cm subsoils have also been acidified appreciably (Johnston et al. 1986b). The additional effect of acidification by the continued use of ammonium sulphate can also be seen on the Park Grass experiment. Plots receiving 144 kg N ha^{-1} as ammonium sulphate every year since 1856 now have a pH of 3.2 and 3.8 in the 0- to 23-cm and 23- to 46-cm depths, respectively (Table 10). As well as dramatically reducing the number of species growing on these plots [two or three compared to about 40 on the control (Tilman et al. 1994)], such intense acidification to depth has implications not only for sustainable land use, but also for drainage water quality. Once soil pH has fallen to about 4.0 throughout the soil profile to the depth at which water moves sideways into drains then it might be expected that this drainage water will contain appreciable amounts of aluminium, iron and manganese (Goulding and Blake 1993).

Even where soil has been subject to acidifying inputs from the atmosphere alone — the unmanured plot of Park Grass — metals have been mobilized and taken up by the herbage (Blake et al. 1994). On the unlimed section of the plot pH (in 0.01 M $CaCl_2$) has declined to about 4.1 and there has been a dramatic increase in the concentration of aluminium, and other metals, in the hay (Fig. 10). On the limed section of the plot there has been no increase in the concentration of aluminium.

CONCLUSIONS

Long-term experiments are essential in determining those factors of soil fertility which affect the sustainability of yield and the need to use fertilizers. It is only over an extended time-scale that any interaction between factors may become apparent. Soil type, management, climate all affect the SOM content, the degree of acidification or the build up of pests and diseases. These, in turn, may influence the efficiency with which additional fertilizer N or available P and K is used or the amounts of metal pollutants which may be mobilized.

Long-term experiments need to be kept under constant review. They may need to be modified so that they are relevant to today's agricultural and environmental concerns (Poulton 1996). Indeed, they *should not be* regarded as museum pieces which can never be changed. As long as their long-term continuity and integrity is not compromised then such experiments can provide ideal sites on which to base modern research, e.g. the siting of ^{15}N microplots within existing plots of known history, measurements of gaseous fluxes or nitrate leaching.

Most importantly, archived samples of crops and soils can be used to follow changes which may not have been envisaged when the experiment started. These have included pH, radiocarbon measurements and, more recently, atmospheric pollutants such as polynuclear aromatic hydrocarbons. Data from archived and fresh samples can be used to construct and validate computer models such as those relating to the turnover of SOM. For further examples see Poulton (1996).

The value of well-managed long-term experiments should not be underestimated. Every effort should be made to make full use of those we have and, in particular, to compare data from those on different soil types and under different climatic conditions.

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