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USING THE LONG-TERM EXPERIMENTS AT ROTHAMSTED TO ADDRESS CURRENT AGRICULTURAL AND ENVIRONMENTAL ISSUES

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In the Broadbalk Experiment at Rothamsted winter wheat has been grown in monoculture since 1843; wheat in rotation and additional treatments have been introduced during the course of the experiment. Since 1968, when new crop varieties and fungicides were introduced, yields have averaged over 6 t ha^{-1} with either inorganic fertilizers or farmyard manure. With high-yielding varieties of winter wheat on Boardbalk, or spring barley on the Hoosfield experiment, maximum yields are currently achieved with a combination of inorganic and organic inputs. The long-term experiments have provided much information on the losses of nitrate and phosphate to water from different treatments and also on the impact of recent decreases of sulphur deposition on soil S dynamics and crop composition. Archived samples of soils and crops from the Park Grass Experiment (continuous cut pasture) and experiments in which arable land has reverted to forest have provided information on soil acidification. This has resulted mainly from acid deposition, previously SO_2 but now dominated by oxides of nitrogen. Acidification has caused the mobilization of toxic metals including Al, Mn and Zn and their increased uptake in herbage. Archived samples have also made it possible to study the deposition and accumulation of metals and organic pollutants in soils and crops and the changes in soil organic carbon and nitrogen content resulting from different management practices. Such data has been used to construct models of soil C and N dynamics. The on-going sites provide experimental material for biological studies including fertilizer and management impacts on nitrous oxide fluxes and for testing hypotheses on soil biodiversity and quality.

KEY WORDS: Long-term experiments, yields, nitrate, phosphate, metals, organic pollutants

DIE NUTZUNG DER DAUERVERSUCHE VON ROTHAMSTED ZUR KLÄRUNG AKTUELLER PROBLEME VON LANDWIRTSCHAFT UND UMWELT

Im Broadbalk Experiment in Rothamsted wurde seit 1843 Winterweizen als Monokultur angebaut. Später wurde Weizen in der Fruchtfolge und weitere zusätzliche Behandlungen eingeführt. Seit 1968, mit neuen Sorten und Fungiziden, ist der Ertrag auf über 6 t/ha angestiegen. Mit dem Anbau von Höchstertragssorten von Winterweizen im Broadbalk- bzw. Sommergerste im Hoosfield-Experiment wird der Höchstertrag gegenwärtig mit einer Kombination organischer und mineralischer Düngung erreicht. Die Dauerversuche lieferten viele wertvolle Informationen, z.B. über die Verluste an Nitrat und Phosphat in das Grundwasser oder auch zum Einfluß der Verringerung der Schwefeldeposition auf die Schwefeldynamik und die Pflanzenzusammensetzung. Archivierte Boden- und Pflanzenproben vom Park Grass

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Experiment (ununterbrochene Mähwiese) und von Experimenten, in denen Ackerland zu Wald umgewandelt wurde, lieferten Informationen über die Bodneversauerung. Diese resultierten hauptsächlich aus der sauren Deposition, jetzt dominieren Stickstoffoxyde. Die Versauerung hat die Mobilisierung toxischer Metalle, einschließlich Al, Mn und Zn und ihre zunehmende Aufnahme in die Pflanzen verursacht. Archivproben machten es auch möglich, die Deposition und Akkumulation von Metallen und organischen Schadstoffen im Boden und in Pflanzen zu studieren und Veränderungen im Gehalt des Bodens an organischem Kohlenstoff und Stickstoff als Folge unterschiedlicher Bewirtschaftungssysteme zu untersuchen. Diese Daten wurden auch zur Ausarbeitung von Modellen der C- und N-Dynamik verwendet. Die laufenden Versuche sind außerdem Untersuchungsbasis für biologische Studien und für den Test von Hypothesen über Biodiversität und Qualität des Bodens.

STICHWÖRTER: Dauerversuche, Ertrag, Nitrat, Phosphat, Metalle, Organische Schadstoffe

INTRODUCTION

This paper gives examples of how long-term experiments at Rothamsted are being used to study agricultural and environmental issues and considers the strengths and limitations of long-term experiments. Inevitably this discussion relates to the issue of agricultural sustainability. Unfortunately the term "sustainable agriculture" has been over used and is often interpreted, incorrectly, in a very narrow way on the assumption that only low input (and hence low output) systems can be regarded as sustainable. Despite this misunderstanding the overall concept is of great importance. The general definition of sustainable development introduced in the Brundtland Report "Our Common Future" (WCED, 1987) captures the spirit of what is meant very clearly: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This objective is sometimes termed inter-generational equity. To apply it to any particular human activity specific issues have to addressed. For an agricultural system to be regarded as sustainable a range of objectives must be met including biophysical, environmental, economic and social.

Biophysical Factors

The primary requirement of a sustainable agricultural system is that acceptable crop yields are maintained over a long period without a trend for them to decrease with time. This does not necessarily mean that the maximum achievable yields are maintained indefinitely and in many situations consistent moderate yields may be preferable to large year-to-year variations. Maintenance of yields implies that relevant aspects of soil quality are being maintained, e.g. supply of plant nutrients, availability of water, physical conditions, minimal soil erosion, biological activity. It also implies that pests, diseases and weeds are kept under control in the long-term: this does not necessarily mean that they are eliminated but rather kept at an acceptable level. It is not only that reasonable yields of crops are required but also they must be of acceptable quality. For food crops this includes being of appropriate nutritional value for humans or animals and having an acceptably low content of potentially toxic substances. It is also necessary that the soil resource is maintained in the long-term, for example by avoiding a depletion of nutrient reserves, acidification, salinization or physical deterioration. Gradual deterioration of the soil resource may not be apparent in crop yields over a period of years or even decades but it is essential that any such trends are detected (or that the risk is appreciated) so that they can be slowed or reversed through changes in management.

Environmental Factors

It is essential that the maintenance of crop yields is not achieved at the expense of deleterious off-site environmental impacts. Impacts on water quality and atmospheric composition are key issues under this heading, in addition to soil degradation discussed above and off-site impacts of soil erosion. For example, it is possible to envisage a situation in which pests and diseases are well controlled, and crop yields maintained, through large applications of pesticides leading to high concentrations of pesticide residues in drainage water. Similar considerations apply to nutrients such as nitrate and phosphate entering drainage water in response to internal cycling in the soil and to inputs whether from fertilizer, animal manure, crop residues or biological nitrogen fixation. This is a particularly difficult issue as most agricultural systems are inherently leaky with respect to nutrients. Simple decreases in fertilizer inputs are often not the most effective way of decreasing leakages.

Although many strategies are now being developed to decrease losses, it seems likely that, in the case of nitrate, it will be impossible to consistently decrease losses in some agricultural situations sufficiently to meet the very stringent limit of 50 mg nitrate per l required in the European Union and many other countries. It is necessary to view agricultural systems in a regional or catchment context as intermittently large losses from one area may be balanced by lower losses elsewhere. Indeed it now seems necessary to plan land use such that the areas which are most sensitive with respect to water quality are deliberately managed to achieve this. Agricultural systems must also be managed such that emissions of environmentally active gases are minimised, including greenhouse gases, ozone depleting gases and those which cause soil acidification when deposited elsewhere. Different environmental goals can sometimes be in conflict – for example some strategies to decrease nitrate loss to water may increase N_2O evolution. Clearly gaseous fluxes need to be assessed on a national or regional basis and inventories calculated; if agricultural sources of a particular gas are small compared to other sources a small increase may be acceptable if it results from decreasing a different environmental problem. An environmental issue that is sometimes overlooked is the impact on agriculture of emissions from other human activities. Examples are given by Powlson and Johnston (1994) of studies using archived samples from the Rothamsted experiments to study the entry into soils and crops of heavy metals and organic pollutants from atmospheric deposition arising from industrial activity. There have recently been indications that oxides of nitrogen or ozone from vehicle emissions in large cities can decrease crop yields in the surrounding agricultural areas.

Economic Factors

Any agricultural system designed to meet biophysical and environmental criteria will only be adopted by farmers if it leads to an economic return. The economic dimension must therefore be taken into account when considering sustainable agriculture. However, economic criteria differ from the biophysical and environmental in that they can change, sometimes considerably and over a short time, either as a result of market forces or government policies on prices, taxation or subsidies. Thus research aimed at developing new agricultural systems should not be constrained by the current economic situation. Indeed, management practices that are desirable from a biophysical or environmental viewpoint are likely to indicate the changes in policy or pricing that could be used to encourage such practices.

Social Factors

Farmers and non-farming members of society are influenced by ethical, cultural and aesthetic considerations. Consequently it is possible to envisage an agricultural system that meets all of the biophysical, environmental and economic criteria but is simply unacceptable by farmers or others. Individual's views on the appearance of the landscape, animal welfare, recycling of sewage or other wastes, are all examples in this area.

Long-term experiments are of immense value in assessing the sustainability of agricultural systems and practices, mainly because many factors that lead to non-sustainability take many years to become apparent. Such experiments are of particular value in studying biophysical and environmental factors although extrapolating from relatively small carefully managed research plots to large areas under routine management has to be done with care. Some of the limitations to be considered are discussed later in this paper. Long-term experiments are of less direct value for assessing economic aspects although there has been a recent attempt to do this using data from a number of long-term experiments worldwide (Barnett *et al.*, 1995). Long-term experiments are of limited value in assessing social aspects.

LONG-TERM EXPERIMENTS AT ROTHAMSTED

Rothamsted currently runs about 20 long-term (>20 years) experiments on 2 sites in south-eastern England. The sites are at Rothamsted on a silty clay loam (Chromic Luvisol) and at Woburn on a sandy loam (Cambic Arenosol); there was formerly a site at Saxmundham on a sandy clay loam (Eutric Gleysol). Average annual rainfall is 600–700 mm. Some of the experiments were set up specifically to study the effects of soil organic matter (SOM) or pH on crop yield, others to assess the value of phosphorus (P) or potassium (K) fertilisers, and another to monitor the persistence of pesticides in soil. Some of those at Rothamsted date back to the middle of the last century (the Classical Experiments) and were set up to answer very simple questions: what were the main nutrient requirements for the crop grown at that time? Many of the oldest experiments were not randomised or replicated. Various statistical methods have been used to interpret data from these experiments (e.g. Dyke *et al.*, 1983; Jenkinson *et al.*, 1994), although developing more sophisticated techniques remains a major challenge (Barnett, 1994). In many cases, however, the observed trends may be so clear as to need no statistical confirmation.

This paper gives examples of how the long-term experiments have been used to investigate current agricultural and environmental issues.

Sustainability of Yield

The Broadbalk Wheat experiment was first sown to wheat in autumn 1843 and has grown wheat on all or part of the field in every year since. The soil is a silty clay loam with about 20–25% clay. The experiment originally comprised 20 treatment strips (each about 6 by 330 m) on about 4.4 ha. It compared soluble mineral salts (especially of nitrogen (N), P, and K), either singly or in various combinations, with farmyard manure (FYM) and an unmanured plot.

The long-term yields of wheat on a few selected treatments are shown in Figure 1. Where 35 t/ha.year of FYM containing about 220 kg N/ha has been applied (not shown in Fig. 1), yields of wheat grown continuously have been almost the same as those with PK+144 kg N/ha, until recently. Yields on all treatments started to decline in the 1920s. Labour for hand hoeing had become scarce and weeds started to reduce yields. In 1926 the experiment was divided into 5 sections, at right angles to the treatment strips and a system of regular fallowing was introduced to control weeds. Yields recovered (Garner and Dyke, 1969) and fallowing 1 year in 5 continued until the 1950s when herbicides were introduced. One section of the experiment

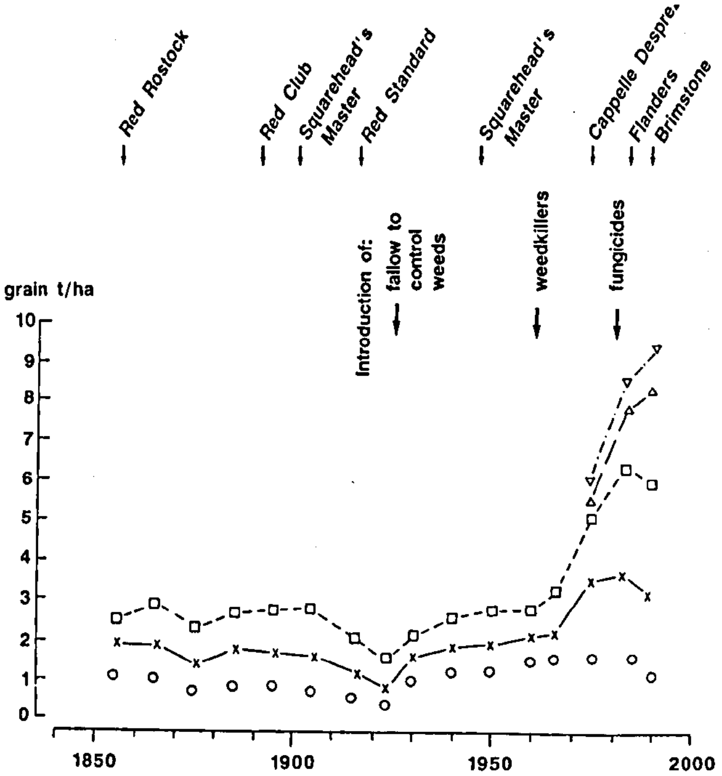

Fig. 1 Yields of wheat on Broadbalk from 1852 to 1990 treated with fertilisers or farmyard manure (FYM) or unmanured, showing the effects of changing cultivar and the introduction of weed control, fungicides, and crop rotation. Treatment: in rotation, ▽ FYM+96 kg N, △ PK fertiliser+144 kg N; continuously, PK fertiliser+□ 144 or × 48 kg N; O unmanured

has never received herbicides; no attempt is made to control weeds, apart from occasional fallowing, and about 80 species of arable weed now provide valuable material for work on herbicide resistance (S. Moss, pers. comm.)

Another change was the introduction of liming. Like many of the arable fields at Rothamsted, Broadbalk had received large, but non-uniform, chalk dressings before the experiment began, and the soil contained up to 5% free $CaCO_3$ (Johnston, 1969). By the early 1950s different treatments and underlying differences in the amount of $CaCO_3$ in the soil had led to considerable variation in pH across the site, with values as low as 4.5 on a few plots. Corrective dressings were applied and regular liming was started to maintain the soil at about pH 7, preventing a decline in yields.

In the above cases of fallowing and liming, the changes were made to ensure that problems with weeds or acidity did not confound the original experimental purpose of investigating the effects of inorganic fertilisers and FYM on yield. It could certainly be argued that the use of ammonium sulphate led to some plots becoming acid and that this was a valid effect that should be measured. However, the effects on soil pH were confounded by the previous chalk dressings, and as the soil is naturally acid, the whole site would have eventually reached a low pH unsuitable for wheat. A test of liming was thought to be inappropriate on this experiment, although such a test became an integral part of the Park Grass experiment (see later).

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 (Tab. I). 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 (Tab. I). With hindsight there might also have been a build up of cereal cyst nematode (*Heterodera avenae*) on this light-textured soil because cereal yields also declined on plots receiving 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. This is an example of how a long-term experiment revealed that a particular agricultural system was not sustainable in a specific situation. In the case of winter wheat at least 20 years of cropping were required before this conclusion could be drawn (Tab. I).

At Rothamsted, soil born pests and diseases, although unknown at the time, were the most likely reason why Lawes and Gilbert were unable to grow legumes and some root crops continuously.

Figure 1 shows the recent dramatic increases in yield in the Broadbalk experiment following two major changes in 1968. The first, and most important in terms of increasing grain yield, was the change to a modern, short-strawed cultivar with a higher grain-yielding potential. Until then, older varieties had been retained in an attempt to relate yield to weather patterns, particularly to rainfall. This was not successful (Yates, 1969). It was then decided that results from the experiment would be

Table 1 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 Treatment [z]	*Period*				
	1877–1886	*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)

more relevant if varieties in current use by the farmers were grown. It is our current practice to change the variety every 5 years, choosing a cultivar that is likely to stay on the recommended lists for that period. The comparative performance of an old, long-strawed variety and a modern, short-strawed variety, was tested in the 1980s by growing the two side-by-side on some sections of Broadbalk (Austin *et al.*, 1993).

The second fundamental change in 1968 was the division into 10 sections and the introduction of rotations on part of the experiment, with the intention of assessing the effects of soil-borne diseases on yield by comparing continuous wheat with wheat after a 2-year break. Figure 1 shows that the effects were considerable, especially when fungicides were applied to protect yield potential.

Effects of Soil Organic Matter on Yield

Figure 2 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 2.5 times as much SOM as inorganic 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. The result was previously used as evidence that the only benefit of FYM was

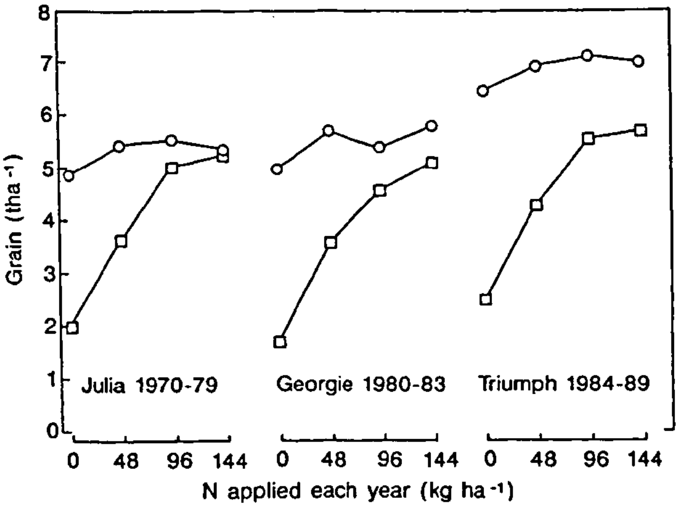

Fig. 2 Hoosfield. Yields of three cultivars of spring barley grown continuously on soils which have received either PK fertilizers (□) or farmyard manure (○) annually since 1852 (Johnston, 1991)

as a source of nutrients; more recent results do not support this conclusion. 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. The likely explanation is that spring-sown crops, with high yield potential, need to grow quickly to achieve good yields and will benefit from improved soil 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 (Fig. 1 and Tab. 2). 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. In terms of sustainability this result highlights a conflict: large inputs of N and the increased soil organic matter content that results from FYM are beneficial for crop yield but lead to large losses of nitrate by leaching. This point is discussed below.

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 being 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.

Table 2 Yields of winter wheat grain (t ha^{-1}) given by fertlizers, farmyard manure and farmyard manure plus fertilizers N, Broadbalk, Rothamsted

	Cultivar grown			
	Flanders 1979–1984		*Brimstone 1985–1990*	
Treatment	*Continously*	*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)

Figure 3a shows changes in soil organic C content on the Hoosfield experiment which began in 1852 and has grown spring barley every year under a range of different fertilizer treatments similar to Broadbalk. As on Broadbalk the SOM content on Hoosfield has been constant for about 100 yr on both the unmanured plot and that given NPK fertilizers (Fig. 3a) (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 temperature climate.

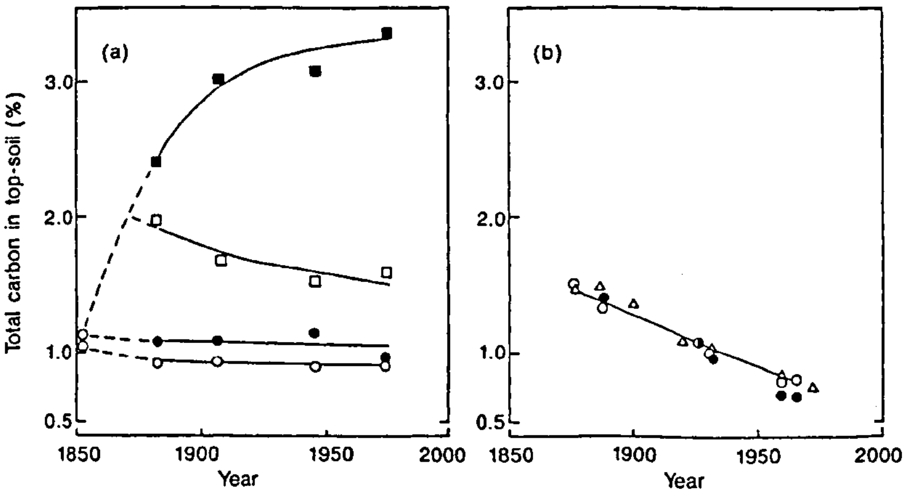

Fig. 3 Total carbon in topsoil, 0-23 cm. (a) Hoosfield, Rothamsted, spring barley each year, annual treatment since 1852, (O) unmanured, (●) PKMg+48 kg Nha^{-1}, (■) FYM, 35 t ha^{-1}, (□) FYM 35 t ha-1, 1852–1871, none since, (b) Woburn, cereals each year (O) unmanured, (●) NPK, (Δ) manured four-course rotation (Mattingly *et al.*, 1975; Jenkinson and Johnston, 1977)

Figure 3b 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 (Figs. 3a,b) (Mattingly *et al.*, 1975). Johnston (1991) gave further examples of the slow build up of SOM under grass and the effects of soil texture in other farming systems at the two sites.

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, as discussed earlier, it is also subject to large losses – by leaching, denitrification and ammonia volatilization. Webster and Goulding (1989) found that denitrification in the Hoosfield spring barley experiment 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 forming legislation which seeks to limit the amounts and

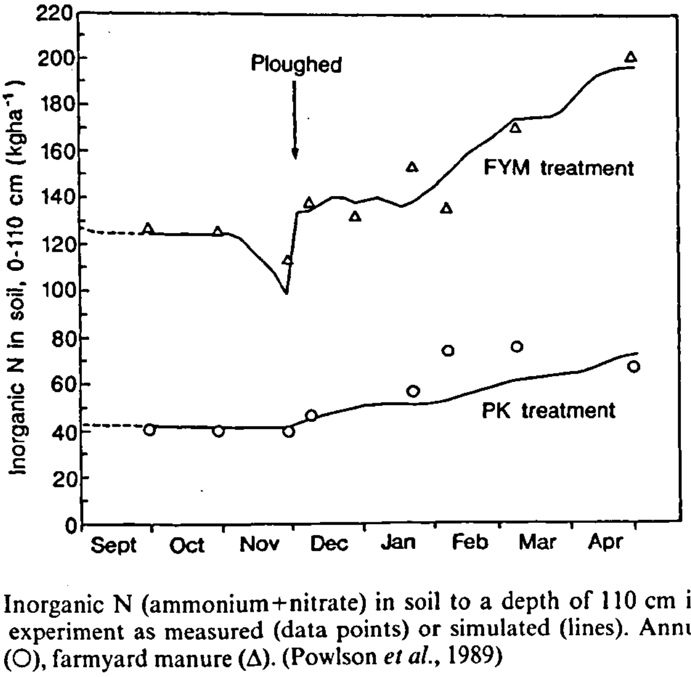

Fig. 4 Hoosfield. Inorganic N (ammonium+nitrate) in soil to a depth of 110 cm in two plots of the Continuous Barley experiment as measured (data points) or simulated (lines). Annual treatment since 1852, PK fertilizers (O), farmyard manure (Δ). (Powlson *et al.*, 1989)

times of application of organic manures and fertilizer N that can be used in areas vulnerable to nitrate pollution.

Developing Models for Soil Carbon Turnover

Data from the long-term experiments have been fundamental in constructing, and validating, the Rothamsted Carbon Model, which simulates the turnover of SOM (Jenkinson, 1987). Figure 5 shows the modelled and measured data for three contrasting treatments on the Hoosfield Spring Barley experiment. Part of the validation involved the analysis of archived crop and soil samples for ^{14}C to see whether the model would accurately simulate the input of labelled C into soil as a result of the atmospheric thermonuclear tests of the 1960s (Jenkinson *et al.*, 1992).

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.

Testing Efficient Use of Nitrogen Fertilizers

Long-term experiments provide excellent sites for the studies on the fate of fertilizer N and N dynamics in soil. Interpretation of the results is simplified if SOM is at equilibrium, i.e. the annual production of soil organic N is equal to the amount mineralized each year. Studies of this type have been conducted because of concern over the movement of nitrate from agricultural soil to water. 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 (Tab. 3) 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

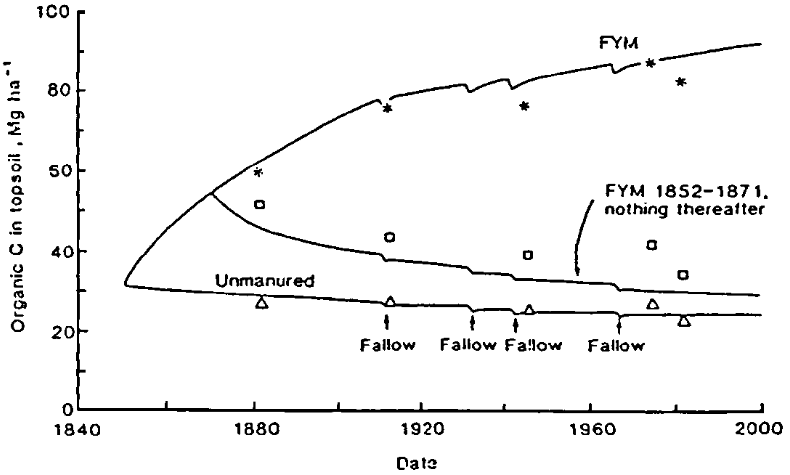

Fig. 5 Organic C in the top 23 cm of soil from three plots of the Hoosfield Spring Barley Experiment, 1852 to 1982: Plot 1-0, unmanured; Plot 7-1, farmyard manure (35 t ha^{-1}) 1852 to 1871, nothing thereafter; Plot 7-2, farmyard manure (35 t ha^{-1}) annually. The symbols show the observations; the lines the model fit (Jenkinson *et al.*, 1987)

Table 3 Percentage distribution at harvest of fertilizer-derived nigrogen applied to winter wheat at 144 kg N ha^{-1} labelled with ^{15}N, Broadbalk, Rothamsted.

	% fertilizer nitrogen			
Year	*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)

soil, grain and straw (Tab. 3), 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 weeks after fertilizer application (Addiscott and Powlson, 1992; Powlson *et al.*, 1992). The losses could have been by volatilization, leaching or denitrification. Denitrification was considered the most likely pathway because rainfall did not exceed evapotranspiration (except for one site in one year) for soils already below field capacity so substantial leaching was unlikely. Soil conditions at the sites were not conducive to ammonia 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 and calculating the impacts of changes in agricultural practice or land use on water quality at the catchment scale.

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 crop growth has been impaired by pests, diseases or drought (see Johnston and Jenkinson, 1989 and Macdonald *et al.*, 1997 for further examples).

Phosphorus

Phosphorus is essential for crop growth. It is taken up, in ionic form, by plant roots from the soil solution where supply must be capable of meeting demand if crop growth is not to suffer (Wild and Jones, 1988). P can be held in the soil in various pools. Some may be readily available to the plant e.g. that extractable by 0.5 *M* $NaHCO_3$ at pH 8.5. Other pools may only be available in the very long term. When annual fertilizer input exceeds annual crop offtake readily-soluble and non-soluble residues accumulate; when offtake exceeds input residues decrease. In cases of both accumulation and depletion the change in the readily soluble pool is only a fraction of the total balance. Table 4 shows the decline in $NaHCO_3$-soluble P as a percentage of crop uptake. Where residues were high the decline in available P was as much as 46% of the balance; where residues were initially low the decline in available P represented only 8% of the balance.

Figures 6a and 6b 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 (or K) to fall below the critical point, thus restricting yield, would certainly mean that nitrogen, either mineralized from SOM or applied as fertilizer or organic manure, 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 in drainage water and problems of eutrophication in surface waters.

It was previously thought that because of the high P fixation capacity of soils, leaching of P through the soil profile was generally of little importance (Cooke, 1976; Ryden *et al.*, 1973). However there is now evidence to suggest that the leaching of P has been underestimated. On some soils at Rothamsted with a long-term history of generous P manuring, balance studies have shown that losses from the system have been greater than was previously thought, with perhaps 20–30% unaccounted for. On the Broadbalk experiment which is drained and from which drainage water samples can be collected, there is further evidence of this loss. Heckrath *et al.* (1995) showed that in soils containing more than c. 60 mg P kg^{-1} of $NaHCO_3$-soluble (Olsen

Table 4 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[a] *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

[a] 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)

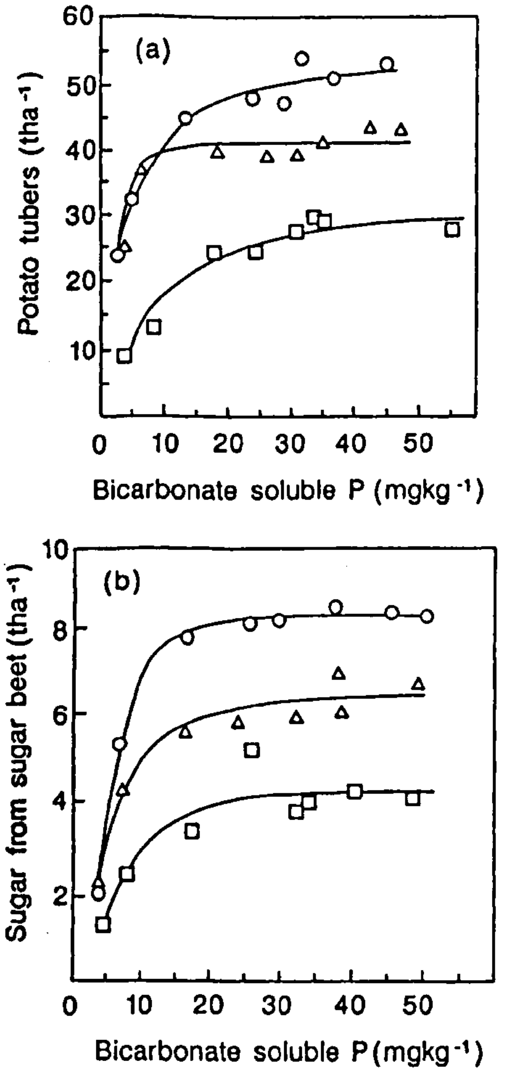

Fig. 6 Relationship between yield and phosphorus soluble in 0.5 M $NaHCO_3$ at Saxmundham. (a) Potatoes (□) 1970; (Δ) 1969, 1972, 1973; (O) 1971, 1974. (b) Sugar from sugar beet (□) 1970, 1974; (Δ) 1972; (O) 1969, 1971, 1973. (Johnston *et al.*, 1985)

P) more P was lost in the drainage water (Fig. 7). Below this value P was strongly retained in the soil.

Fluxes of Methane Between Soil and Atmosphere

Aerobic soil is a significant sink for methane (CH_4), a greenhouse gas that accounts for about 15% of current radiative forcing. Bacteria in soil oxidise CH_4 to carbon dioxide (CO_2), a much less potent greenhouse gas; each molecule of CH_4 is 21 times more radiatively active than one of CO_2. Soil oxidation is estimated to account for 10–15% of global CH_4 destruction, but recent research has shown that land use and agricultural practice have major effects on the rate of oxidation. Long-term experi-

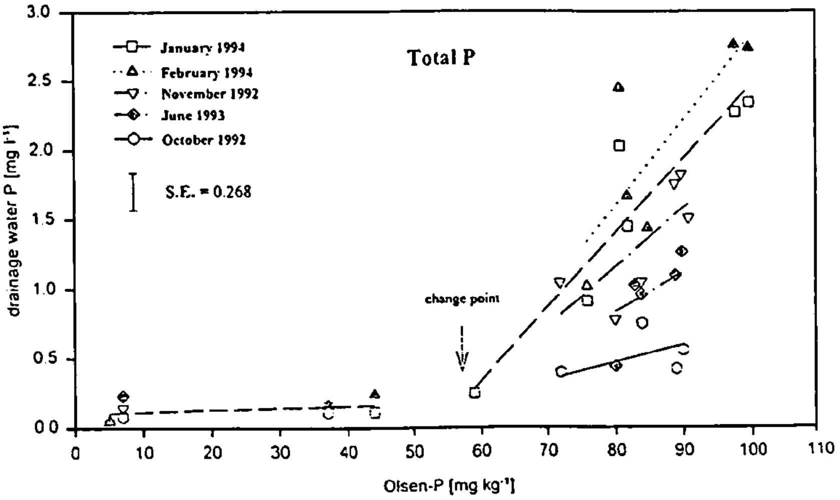

Fig. 7 Relationship between total P (TP) in drainage water and Olsen-P from different Broadbalk plots. The Split-Line Model shown fitted a common initial line and change point (at 57 mg Olsen-P kg^{-1}) but separated changes in slope in the steep section for the five drainage events (90% of the variance accounted for). (Heckrath *et al.*, 1995)

ments have been essential for quantifying these effects and seeking to understand the underlying mechanisms. Figure 8 (taken from Hütsch *et al.*, 1993) shows the oxidation of methane by soil cores taken from 3 plots of the Broadbalk experiment. Application of inorganic N fertilizer greatly decreased oxidation rate compared to the soil never receiving N fertilizer. Although there is a small immediate effect of added N, the main impact is a long-term one. When soils were sampled one year after the last N application the effect was clear and persisted even if N was withheld for several years (Goulding *et al.*, 1995).

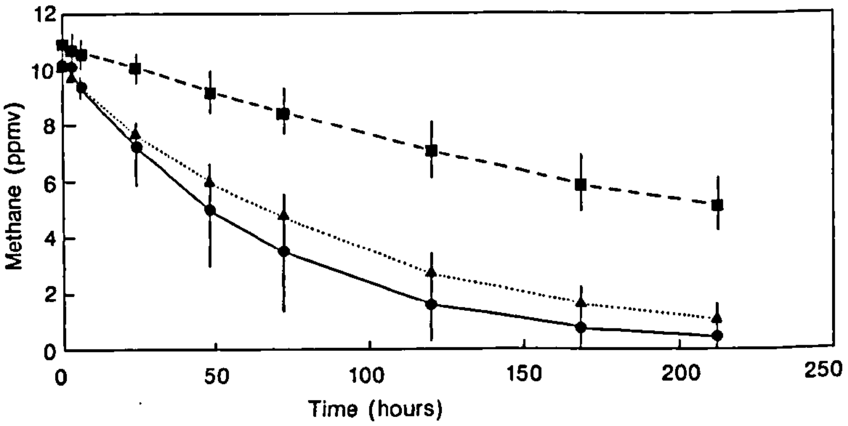

Fig. 8 Methane uptake by soil at Broadbalk (i.e. decrease in methane concentrations in an amended atmosphere during an incubation experiment). ΔPKMg fertilizer since 1852, ■ PKMg + 144 kg N/ha since 1852, ● farmyard manure at 35 t/ha since 1843. Vertical lines represent standard deviations. (Hütsch *et al.*, 1993)

Comparisons have been made of methane oxidation rates on plots of the Park Grass experiment at Rothamsted receiving N as either ammonium sulphate or potassium nitrate but maintained at equal pH by liming. A long history of nitrate applications had no effect on methane oxidation whereas ammonium was extremely inhibitory (Willison *et al.*, 1995). The impacts of land use and soil pH on CH_4 oxidation are even greater than those of N fertilizer. Highest rates are usually found in undisturbed soils under forest, slightly lower rates under grassland and the slowest rates in arable soil.

These comparisons have been possible because of the use of long-term experiments at Rothamsted (Willison *et al.*, 1995) and Bad Lauchstadt (Willison *et al.*, 1996). There is now considerable evidence that the changes in CH_4 oxidation rate result from differential effects of N input, soil pH and soil disturbance on methanotrophs and ammonium oxidising bacteria (nitrifiers), both of which can oxidise methane. It seems likely that nitrifiers are mainly responsible for oxidation in disturbed (i.e. arable) soils and perhaps in managed grasslands but that methanotrophs are more important in undisturbed forest soils (Goulding *et al.*, 1995; Willison *et al.*, 1995, 1996).

Soil Acidification

Much use has been made of archived samples of soil and plant material. The sample archive at Rothamsted contains > 250,000 samples dating back to the middle of the 19thC. They can be used to quantify changes in soil constituents retrospectively using modern analytical methods. For example they have allowed us to look at the effect of vegetation on the rate of soil acidification and the mobilisation of heavy metals.

The Park Grass experiment was started in 1856 on a site thought to have been in grass for several hundred years (Warren and Johnston, 1964). Two plots have remained unmanured since then. Initially the 0–23 cm depth of soil had a pH (H_2O) of about 5.6. Less than 1 km away (on the same soil type) is the Geescroft Wilderness. This was part of an arable experiment until it was fenced off in 1885, at which time pH was about 7.1. Since then, the site has been left undisturbed, and a mature, deciduous woodland has developed. Table 5 shows the pH changes under the two types of vegetation.

Acidification arising, at least in part, from aerial pollution has been faster and more intense on Geescroft than on Park Grass (in the top 23 cm, about three pH units in 100 years *v.* one pH unit in 140 years). Other causes of soil acidification, at or near neutral pH values, are the natural inputs of H^+ from the dissolution of CO_2 and subsequent dissociation of carbonic acid, and the mineralisation of organic matter. These processes will become less important as pH falls. The difference between the two sites is that the tree canopy is more efficient at trapping aerial pollutants than the low-growing herbage. Under the trees, the subsoils have also acidified appreciably (Johnston *et al.*, 1986a). The additional effect of the long continued use of ammonium sulphate fertiliser can also be seen on Park Grass where there has been considerable acidification of both top and subsoil.

Metals have been mobilised and taken up by the herbage even where soil has been subject to acidifying inputs from the atmosphere alone, i.e. on the unmanured plot of Park Grass (Blake *et al.*, 1994). Figure 9 shows that, on the unlimed portion of the plot, the pH (measured in $CaCl_2$) has fallen to about 4.1 and there has been a

Table 5 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.*, 1986 b)

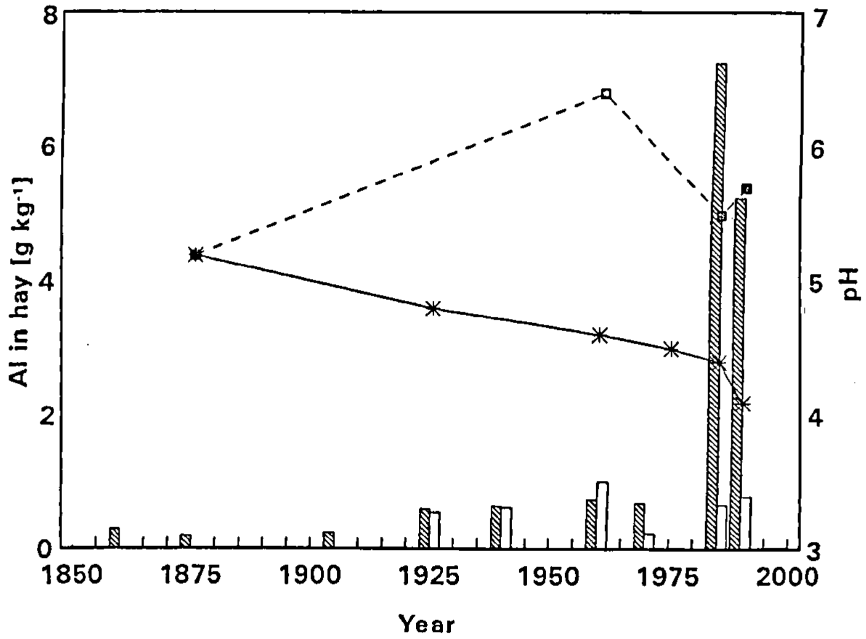

Fig. 9 Park Grass. Aluminium (Al) in hay from unlimed (▨)and limed (☐) sections of plot 3 and its relationship to pH (in $CaCl_2$) in soil from the 0 to 23 cm layer of the unlimed (*) and limed (■) sections. (Blake *et al.*, 1994)

dramatic increase in the concentration of aluminium, and other metals, in the hay. On the limed part of the plot, the pH has been maintained at a higher level, and there has been no increase in the concentration of aluminium in hay.

Pollutants in Soils and Crops

Archived samples have been used to examine organic pollutants deposited from the atmosphere such as polynuclear aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), and dioxins (Jones *et al.*, 1989a, 1989b; Kjeller *et al.*, 1991; Wild *et al.*, 1992). Figure 10, for example, shows how the dioxin content of the soil on Broadbalk has increased during the last century. Measurements such as these were inconceivable when the earlier samples were collected and archived. Similarly inputs of metals including Cd, Zn and Pb into soils and crops have been studied and the relative importance of atmospheric deposition, inorganic fertilizer or organic manure assessed.

Opportunities and Limitations for Carbon Sequestration in Soils

Globally, soil organic matter (SOM) is estimated to contain about 1500 Pg of C (Eswaren *et al.*, 1993; note that 1 Pg = 10^{15} g) which is twice the 750 Pg held in atmospheric CO_2. Consequently small changes in the soil stock of organic C could have a significant effect on atmospheric CO_2 concentration. Deforestation in the tropics not only releases CO_2 from trees but also from SOM as this continues over periods of years or decades. There is much interest in the extent to which carbon might be sequestered in soil as a means of mitigating the increase in atmospheric CO_2 (Cole *et al.*, 1996). This might be achieved through altered management of agricultural areas. Long-term experiments are the ideal means of quantifying slow changes in SOM and comparing different land use or management scenarios. It is not feasible to conduct such experiments under the full range of climates and situa-

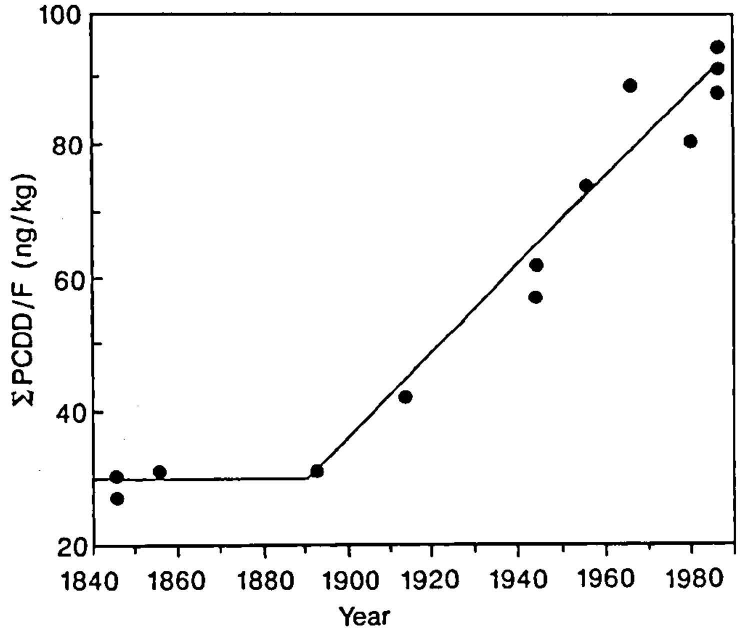

Fig. 10 Trends in the concentration of polychlorinated dibenzo-p-dioxin and -furan (ΣPCDD/F) in the top 23 cm of soil on the unmanured plot of Broadbalk between 1846 and 1986. (Adapted from Kjeller *et al.*, 1991)

tions of interest or to cover the full range of possible scenarios. Furthermore, information is required quickly; whilst the setting up of new long-term experiments is an extremely important investment for the future, it is not an option for providing answers to current questions. The only feasible way of testing scenarios is to use SOM models and the only means of testing a model's validity is to compare its output with data from long-term experiments. Once a model has been evaluated in this way it is reasonable to use it more widely, taking note of any limitations that were revealed by the evaluation exercise. To facilitate this process of model evaluation a global network has been established which currently contains metadata on soil C from more than 70 long-term experimental sites and some 20 SOM models (Smith *et al.*, 1996). The network is known as GCTE-SOMNET (Soil Organic Matter Network) and the directory of long-term sites and SOM models can be accessed on the World Wide Web at URL http://yacorba.res.bbsrc.ac.uk/cgi-bin/somnet.

At a model evaluation workshop held within the content of GCTE-SOMNET, 9 models attempted to simulate 12 datasets from 7 long-term experiments (Powlson *et al.*, 1996). The results of this exercise are reported in a special issue of *Geoderma* (Smith *et al.*, 1998).

LIMITATIONS OF LONG-TERM EXPERIMENTS

Many older experiments were not replicated. Large plots (which were a feature of most of the early Rothamsted experiments) give us confidence that effects are real and not an artifact resulting from position in the field. Recent developments in environmental statistics derived, in part, from long-term experiments, increase our confidence in the data (Barnett, 1994). Obviously, any new experiment should be statistically sound, normally involving a replicated and randomized design although other approaches are possible.

Plots should be as large as possible to allow for proper management with farm machinery and to allow for future sub-division if necessary. In arable situations large plots also help to minimise the effect of soil movement which is always a potential problem (Sibbesen *et al.*, 1985). Ploughing and/or other cultivations should be along the length of the plot, not across, with soil being turned in one direction one year and the opposite direction the following year. On the Broadbalk Continuous Wheat experiment, which is ploughed every year, the effect of soil movement can be seen by taking a transect across plots receiving different amounts of P. Figure 11 clearly shows the considerable gradient in soil total P content across the 1.5 m paths between plots and extending about 1 m into each plot (A, B, C). It also shows that there is a region of approximately uniform P content in the central part of each plot. Obviously any soil or crop sampling should be done within this central area. In contrast, on a lighter-textured soil at Woburn where there has been cross cultivation, the gradient extends across the entire widths of the plots (D, E, F, G) and there is no plateau. In such situations, a complete nutrient balance may not be possible. However the site may still be useful if the current requirement is for comparing crop growth, yield, etc at different ranges of P. In some cases a gradient in a particular

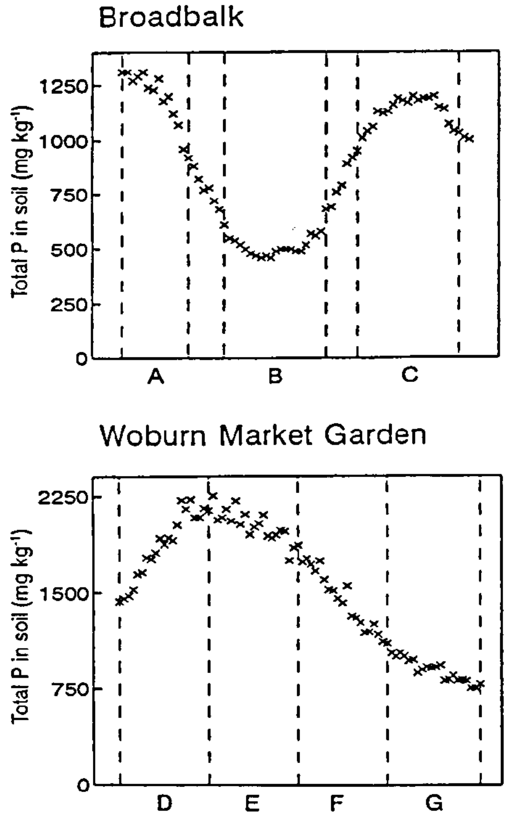

Fig. 11 Total P in the top 23 cm of soil along a transect across plots given different P treatments. Broadbalk: A, FYM 35 t ha^{-1} yr^{-1} containing *c.* 40 kg P; B, unmanured; C, PK fertilizers supplying 33 kg P ha^{-1} yr^{-1}; all since 1843. Plot A is 4 m wide and is immediately adjacent to another FYM treatment; plots B and C are 6 m wide. Woburn Market Garden: total amounts of P, kg ha^{-1}, applied between 1942 and 1967, E, 13 130 kg in sewage sludge; F, 7720 kg in FYM; in addition all plots, D E F G, received 1000 kg P ha^{-1} as superphosphate between 1942 and 1984. Plots are 5.2 m wide (Adapted from Leigh *et al.*, 1994)

soil property may provide a valuable experimental facility. The site is also a valuable resource for experiments designed to test hypotheses and which require contrasting, but stable, soil properties to have been established over a long period.

Where the site is not being cultivated, as in grassland experiments, soil movement is unlikely to be a problem. However, the accurate application of treatments over many years is equally important and is dependent on careful attention to avoid errors. On the Park Grass experiment which started in 1856 the sharp boundaries between plots can be clearly seen. Transects taken across these boundaries show gradients, e.g. in pH status which extend < 0.5 m into the plot (Fig. 12).

Relevance to Current Issues

Long-term experiments should not be regarded as unchangeable museum pieces. Indeed, they should be modified to make them as relevant to today's agriculture and environmental concerns as possible without losing the long-term continuity and

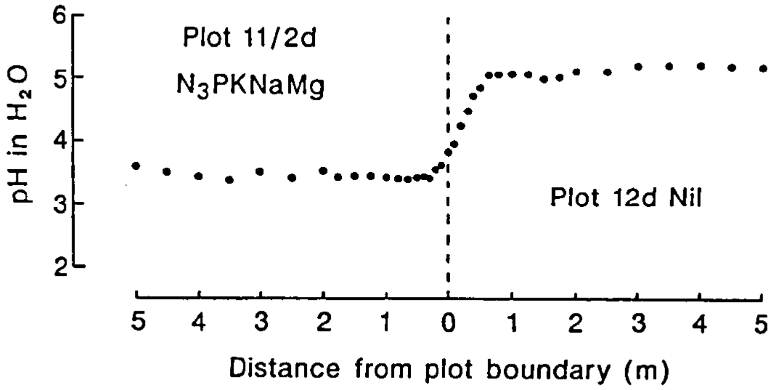

Fig. 12 Park Grass: pH in the top 23 cm of soil along a transect across the boundary between plots receiving different treatments. 12 d nil; 11/2 d, N_3, P, K, Na, Mg fertilizers supplying 144 kg N ha^{-1} yr^{-1} as ammonium sulphate since 1856

integrity of the experiment. However, they should not be changed just to provide answers to short-term problems which could be studied elsewhere. Any change must be well documented. This paper shows how the experiments at Rothamsted have been modified or adapted to provide data which is of immense value to farmers, scientists and policy makers. For those scientists studying the sustainability of different systems or constructing models to be used in predicting the effects of global change there is a need for much more data from long-term experiments conducted over a wide range of soil types and climatic conditions for validation. In this respect the networking of long-term sites world-wide is of great importance. The development of GCTE – SOMNET is one example of this. Another example is the deductions that were possible by comparing results on the biological effects of heavy metals in soils using two sewage sludge experiments in Germany and one in the UK (Chaudri *et al.*, 1993).

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