The Rothamsted Classical Experiments

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Introduction

Many European countries are undergoing changes in agricultural practice. In the EC for example current policy seeks to curtail the over-production of cereals by the use of set-aside whilst in Central Europe it is clear that the recent political and economic developments will have a major impact on the agriculture of this region and that changes in farming practice are inevitable. Throughout Europe concern about the environment and the effects of agriculture upon it continue to grow. It is appropriate, therefore, to consider how these changes and concerns may affect soil fertility and the sustainability of food production.

Defining soil fertility in biological, chemical and physical terms is not easy but crop yield can be used to indicate the sustainability of a particular system because the crop integrates across all those factors affecting its growth. Crop yield does not necessarily give advance warning of factors that will lead to non-sustainability. It would be valuable to have a soil property that achieved this but, as yet, no single factor has been identified and it is unlikely that such a simple index is likely to be found. In different situations any one of a range of different factors may become limiting. Soil fertility and productivity are discussed by JOHNSTON (1991a). Many aspects of soil fertility such as acidity or soil organic matter may change slowly with time. By using data from long-term experiments we can begin to address some of the current concerns.

In this paper we take examples from long-term experiments at Rothamsted where the soil is a silty clay loam (c. 20% clay) and annual rainfall is 700 mm and Woburn, a sandy loam (c. 10% clay) with 600 mm rainfall.

Evidence for Sustainable and Non-sustainable Production

The Broadbalk Continuous Wheat experiment was first sown in autumn 1843 and wheat has been grown on all or part of the field every year. Figure 1 compares the yields given by farmyard manure (FYM), 35 t ha^{-1}, and NPK fertilizers 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. Yields on plots given either FYM or 144 kg N ha^{-1} plus PK fertilizers have remained essentially equal throughout the whole period of the experiment. On soils given only inorganic fertilizers, soil organic matter has increased only slightly compared to the unmanured plot during the last 100 years; a maximum increase of about 15% due to larger returns of organic matter in stubble or

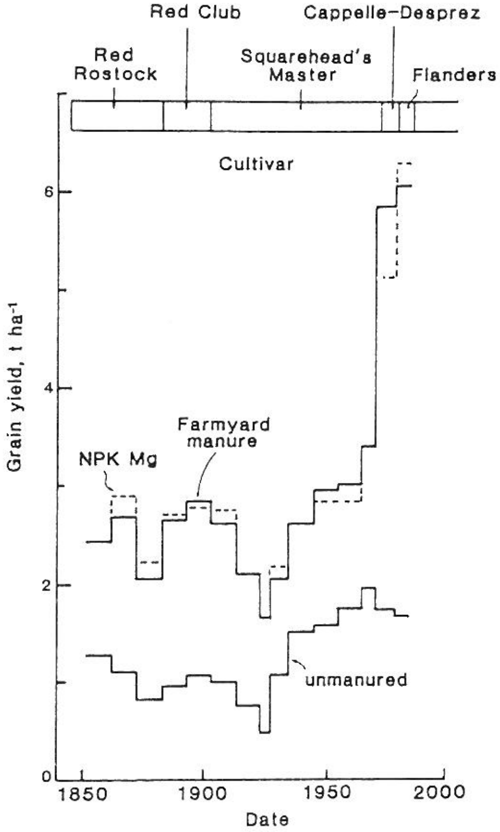

Figure 1

Yields of winter wheat, Broadbalk, 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} and 210 kg K ha^{-1})

roots. 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.

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 minor extent, crop growth removing calcium. Soil acidification is a world-wide problem and can have a major effect on sustainable land use especially if it mobilizes heavy metals (BLAKE et al., 1994).

Effects of soil acidity on crop yield

In contrast to the sustainability of cereal yields at Rothamsted, yields of barley, and to some extent wheat, grown continuously on the sandy loam at Woburn began to decline about 15 years after the experiments started in 1876 (Table 1). 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. 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 1). With hindsight there may also have been a build up of cereal cyst nematode on this light textured soil because cereal yields also declined on plots getting sodium nitrate, which had little effect on soil pH (JOHNSTON & CHATER, 1975), and did not decline where cereals were grown in rotation on adjacent experiments.

At Rothamsted, the soil had as much as 5% free $CaCO_3$ when the experiments started, and the use of ammonium sulphate, supplying up to 144 kg N^{-1} yr^{-1}, caused no serious problem with soil acidification until the late 1940s and early 1950s. 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.

Table 1

Yields of wheat and barley grain, t ha^{-1}, and the effect of chalk on plots given ammonium sulphate (Continuous Wheat and Barley Experiments, Woburn 1877-1926)

Crop and treatment[a]	1877-1886	1887-1896	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
NPK - chalk [b]	-	-	-	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
NPK - chalk	-	-	1.39	1.39	0.90
FYM	2.39	2.30	1.87	1.87	1.54

Remarks:

[a]: 46 kg N ha^{-1} as ammonium sulphate, FYM 17.6 t ha^{-1} per year on average;

[b]: 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; Applying chalk would have raised soil pH more soon after application.

Table 2

Yields, t ha^{-1}, of turnips and winter wheat in the Agdell Rotation Experiment, Rothamsted 1848-1951

Years	Crop and treatment			
	Turnip roots		Wheat grain	
	None	NPK	None	(NPK)*
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		

* NPK fertilizers were applied only once every four years to the turnips. Wheat followed a one year clover ley which would have left a nitrogenous residue

Problems did occur, however, on the Four-course Rotation experiment on Agdell field which started in 1848 (JOHNSTON & PENNY, 1972). Turnips, spring barley, clover or beans and winter wheat were grown in rotation. Increasing soil acidity after 80 years allowed Club root (caused by the fungus (*Plasmodiophora brassicae*) to flourish and so decreased turnip yields (Table 2) that the experiment had to be stopped in 1951. Yields of winter wheat were not affected so seriously (Table 2).

Effect of vegetation on rate of soil acidification

One plot of the Park Grass experiment at Rothamsted which started in 1856 has been unmanured since then. Initially the 0-25 cm depth of soil had a pH about 5.6. Less than 1 km away 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 3 shows that surface soil pH is now about 4.8 on the Park Grass plot and 4.0 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 years on Geescroft, than on Park Grass, about 1 pH unit in 140 years. The inference must be that the tree canopy is more efficient in trapping aerial pollutants than low growing herbage. Under the trees the 23-46 cm and 46-63 cm subsoils have also been acidified appreciably (JOHNSTON et al., 1986).

Table 3

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[a]	0-23	4.2	3.8	3.7	3.4	3.2
	23-46	6.3	4.4	4.1	4.0	3.8

a: 144 kg N ha^{-1} as ammonium sulphate each year since 1856

The additional effect of acidification by the use of ammonium sulphate can also be seen on Park Grass. 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 0-23 cm and 23-46 cm depths, respectively (Table 3). 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 laterally into drains then it might be expected that this drainage water will contain appreciable amounts of aluminium, iron and manganese (GOULDING & BLAKE, 1993).

Soil organic matter (SOM)

In any farming system, soil organic matter or humus content changes towards an equilibrium value that depends on:

1) the quantity of added organic material,
2) its rate of decomposition,
3) the rate of breakdown of existing humus,
4) soil texture; humus is stabilized on clay sized particles, and
5) climate.

The effects of these variables on both C% and N% in the top-soil has been assessed in long-term experiments at Rothamsted and Woburn. Most soils will not be in equilibrium; the level of organic matter will be increasing or decreasing depending on the management in use at that time.

Figure 2a shows that on Hoosfield soil carbon has been constant for about 100 years on both the unmanured plot and that given NPK fertilizers. 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 soil carbon, 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 years for this medium textured soil in a temperate climate.

Figure 2b clearly illustrates the importance of soil texture on equilibrium levels of carbon. 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 carbon in soils at Woburn than at Rothamsted due to long periods under grass at Woburn (see JOHNSTON, 1991b) but under continuous arable cropping there is now less in Woburn soil.

Although in temperate climates the humus 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 at IITA (Nigeria) than at Rothamsted. With hindsight it is unfortunate that the well-founded Rothamsted results on the slow changes in SOM and

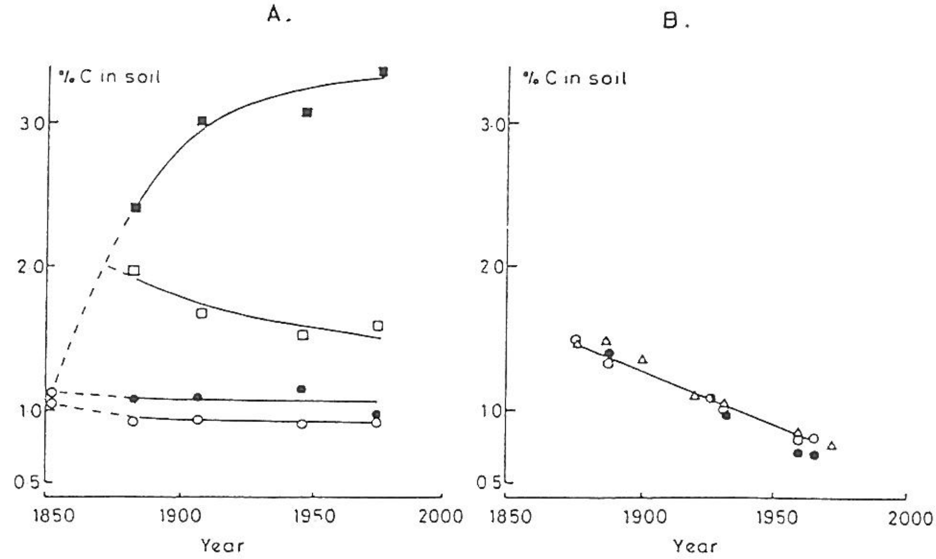

Figure 2

Changes with time in C% in A. Rothamsted soil growing continuous cereals and B. Woburn soil growing continuous cerals and a 4-course rotation of arable crops.

A. Barley each year: o Unmanured; • NPK fertilizers (48 kg N ha^{-1} $year^{-1}$); ■ FYM 35 t ha^{-1} $year^{-1}$; □ FYM 1852-1871 none since. B. Cereals each year: o Unmanured; • NPK fertilizers; Δ Manured 4-course rotation

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.

Effects of soil organic matter on yield

The effects on crop yield of maintaining SOM became apparent much earlier on the sandy loam at Woburn. Several experiments were set up to investigate these effects; one, the Woburn Ley-Arable experiment started in 1938. In this experiment some plots are in a continuous arable sequence, others are in a rotation with grass or grass/clover leys. The soils now contain c. 0.8% C and 1.1% C, respectively.

Figure 3 shows the yield of winter wheat, in two 5-year periods, in either the continuous arable situation or following a 3 or 8-year grass ley or a 3 or 8-year grass/clover ley. Where no fertilizer N was applied grain yields were increased by c. 1.5 t ha^{-1} following grass leys and a further 1 t ha^{-1} following grass/clover leys, compared to wheat in the continuous arable rotation. These increases can be attributed to the extra N mineralized from the soil organic matter following the ploughing in of the grass leys and to the more readily available N residues following the clover. Wheat given 70 kg N ha^{-1} following grass/clover leys yielded as much as wheat in the continuous arable sequence given 210 kg N ha^{-1} (POULTON, pers. commun.).

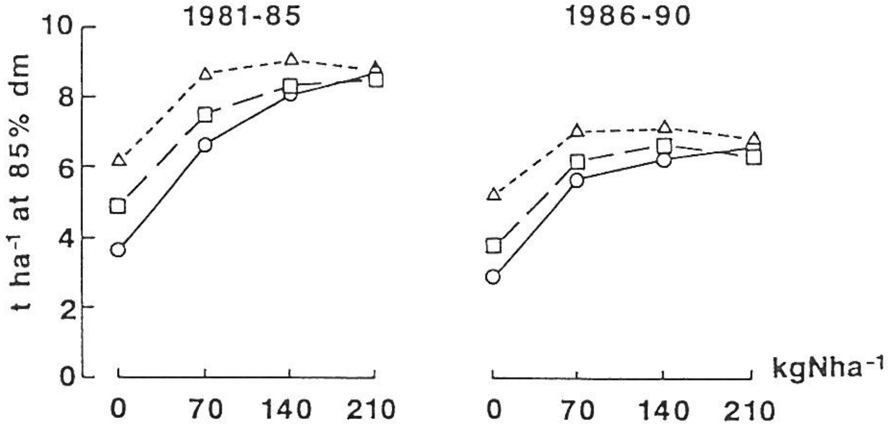

Figure 3
Yields of winter wheat in two 5-year periods after various rotations. Woburn Ley-Arable. o: continuous arable;□: 3 or 8-year ley; Δ: 3 or 8-year grass/clover ley.

At Rothamsted the benefits of extra organic matter for cereals have only become apparent when modern varieties with a higher yield potential have been grown; and where that potential has been protected.

Figure 4 shows the grain yield 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 and FYM 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 inorganic N. In the first period, 1970-79, 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 1980-83 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, 1984-90, cv Triumph, yielded little more on fertilizer-treated soils than cv Georgie in the previous period, but much more on FYM-treated soil.

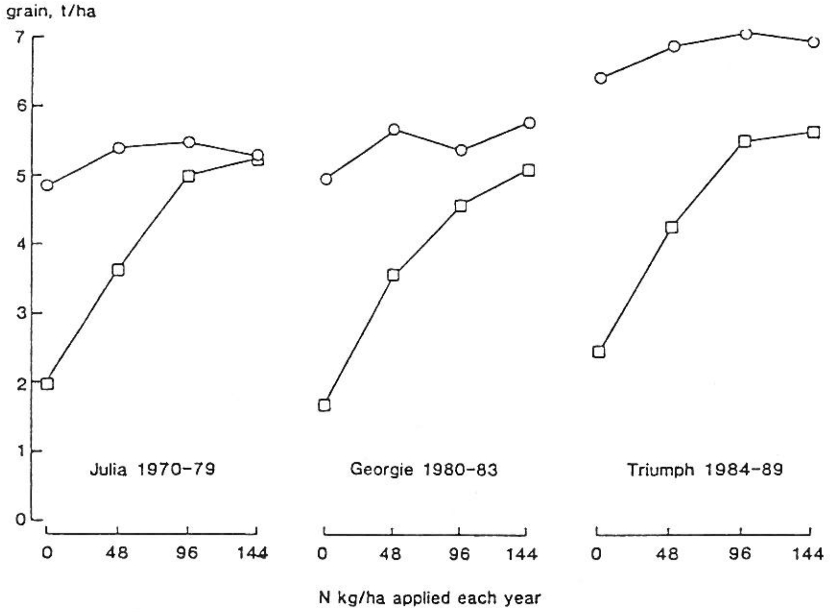

Figure 4
Yields of three cultivars of spring barley grown continuously on soils which have received either PK fertilizers (□) or farmyard manure (o) annually since 1852 (Hoosfield).

Clearly spring sown crops, with high yield potential, have to grow quickly to achieve good yields and this requires good soil physical conditions for rapid root growth to explore the soil for nutrients and water. A similar benefit of having extra organic matter in soil is now also seen for autumn sown winter wheat on Broadbalk (Table 4). In recent years yields have always been largest when

Table 4
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**	**Continuously**	**In rotation**
NPK[a]	6.93	8.09	6.69	8.61
FYM	6.40	7.20	6.17	7.89
FYM + N[b]	8.13	8.52	7.92	9.36

[a]: Best yields of cv Flanders were given by 192 kg N ha^{-1} and of cv Brimstone by 288 kg N ha^{-1}; [b]: FYM plus 96 kg ha^{-1} fertilizer N

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. But, where extra fertilizer N is given in spring the better conditions which exist on the FYM-treated soil results in a yield which cannot be matched on the other plots by inorganic fertilizers alone.

Effect of different rotations

The reason why Lawes and Gilbert started their experiments with arable crops grown in monoculture has been discussed elsewhere (JOHNSTON & 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.

Observations of the incidence of take all, caused by *Guamannomyces 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 ten sections. On some sections wheat was grown continuously, on others after a two-year break from cereals, which was known to minimize any risk of take all affecting the next crop. Yields during the next 15 years are shown in Figure 5. From 1970-1978 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 with more N; after a two-year break, yields peaked at 96 kg N ha^{-1} and then declined. When 96 kg N ha^{-1} was given the benefit of the two-year break was 1.8 t ha^{-1} grain. On plots with more organic matter from repeated applications of FYM, the two-year 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}). At this level of N the benefit of the two-year 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. The effect of breaking take all decline by having a two-year break and then three consecutive wheats has been tested since 1985. With fertilizer, FYM and FYM+N, best yields of the third wheat after a two-year break were always less than those of wheat grown continuously (Table 5) because after a two-year

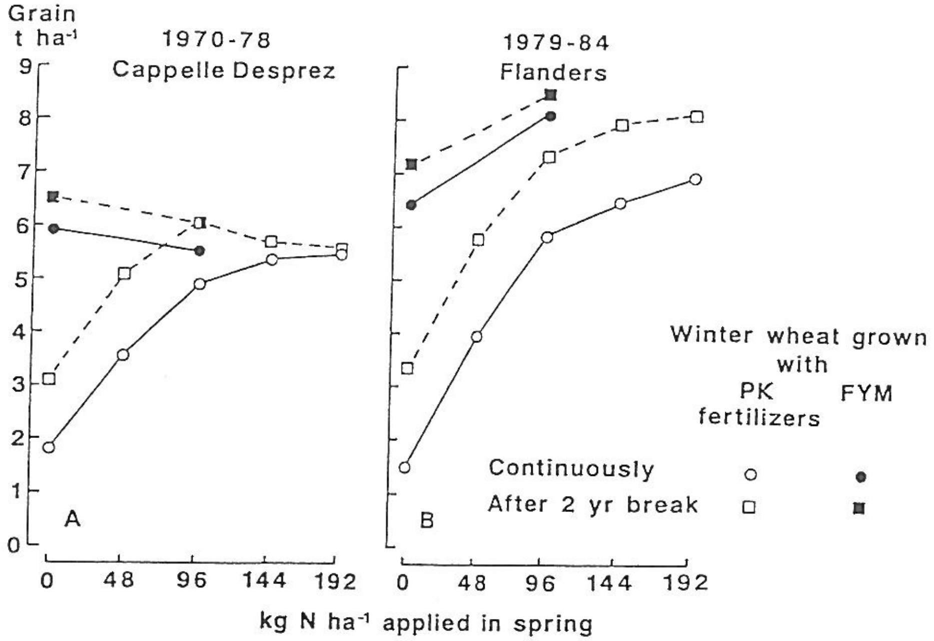

Figure 5
Yields of two cultivars of winter wheat grown continuously or after a 2-year break on soils which have received either PK fertilizers or farmyard manure annually since 1852 (Broadbalk)

break from cereals the causative agent for take all decline built up less quickly than *Guaemannomyces 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

Table 5
Yields of grain, t ha^{-1}, of first, second and third wheat after a 2-year break compared with wheat grown continuously (Broadbalk, Rothamsted, 1985-1990)

Treatment	Wheat after a 2-year break			Continuous wheat
	First	Second	Third	
NPK[a]	8.61	7.85	6.47	6.69
FYM	7.89	5.86	5.37	6.17
FYM + N[b]	9.36	8.64	7.59	7.93

[a]: Best yield of cv Brimstone was given by 288 kg N ha^{-1}; [b]: FYM plus 96 kg ha^{-1} fertilizer N

also an important message for farmers, namely that whilst it 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 two-year break.

Testing efficient use of nitrogen fertilizers

Environmental concern over nitrate in potable water supplies led to research into the efficient use of fertilizer N. This could best be done using labelled ^{15}N fertilizer on a site where there was no net accumulation or decline of soil organic N. This situation only occurs in long-term situations where soil organic matter levels are in equilibrium. POWLSON et al. (1986) described experiments made during four years on Broadbalk, in which varying rates of ^{15}N-labelled fertilizers were applied to winter wheat. Averaged over four years c. 20% of the spring applied N fertilizer was found in the soil after harvest (Table 6) but less than 2% of the total applied was present as mineral N; most was there as organic N. The N balance for these experiments (Table 6) 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 in the three weeks after fertilizer application (POWLSON et al., 1992; ADDISCOTT & POWLSON, 1992). The losses could have been by volatilization, leaching or denitrification. In this case the latter was most likely because, except for one site in one year, rainfall did not exceed evapotranspiration for soils already below field capacity. 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

Table 6

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 in			
	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

measurement (GOULDING, 1990). Such inputs need to be identified and allowed for when making fertilizer recommendations.

These results confirmed the belief that most of the nitrate present in soil in autumn comes from the mineralization of organic matter, an important observation for those framing legislation on N fertilizer use. Exceptions are where N has been applied in excessive amounts relative to the yields potential of the site for a particular crop or where the crop has failed for some reason.

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 soil organic matter 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 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. 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 trials, e.g. the use of ^{15}N, 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 measurements of pH, radiocarbon and, more recently, atmospheric pollutants. Data from archived and fresh samples can be used to construct and validate computer models such as those relating to the turnover of soil organic matter.

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.

Summary

The sustainability or otherwise of differently managed systems can be demonstrated using results from long-term experiments at Rothamsted and Woburn. Examples are given of the effects on crop yield of increasing acidity and of soil organic matter. The influence of SOM, soil-borne pathogens and cultivar are also discussed in relation to fertilizer N efficiency. [This paper is based on JOHNSTON & POWLSON (1994) and POWLSON & JOHNSTON (1994).]

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