Rothamsted Experimental Station – 150 Years of Agricultural Research

The Longest Continuous Scientific Experiment?

DR JOHN A. CATT and DR IAN F. HENDERSON

AFRC Institute of Arable Crops Research, Rothamsted Experimental Station, Harpenden, Herts., UK

In 1993, Rothamsted Experimental Station, the oldest agricultural research institute in the world, celebrated 150 years of experimental work on the production of farm crops. Most of the station's 'classical experiments', begun by its founder John (later Sir John) Lawes between 1843 and 1856, continue today and provide useful information for contemporary agriculture and ecology which Lawes could never have envisaged. These include development of a model for the turnover of organic matter in soil, assessments of the increasing pollution of soil by toxic metals and organic carcinogens resulting from twentieth century industrial activities, and insights into the ecological consequences of changes in agricultural policies. The experiments also provide many examples of the value of long term, systematic data collection and interdisciplinary research in agricultural production, ecology and environmental pollution. Facilities for this work became available through the scientific flair and foresight of Lawes, and since his death have been maintained and extended by generations of dedicated scientists.

Agriculture has always been one of the most interdisciplinary of the sciences. Efficient food production without causing environmental pollution involves knowledge of subjects as diverse as, for example, the movement of water carrying plant nutrients or pesticides through soil pores and the production of monoclonal antibodies to distinguish closely related viruses responsible for plant diseases. Modern agricultural research institutes, such as those of the Agricultural and Food Research Council in the UK, consequently employ a wide range of highly specialised chemists, physicists, mathematicians, engineers, microbiologists, zoologists and other scientists. However, when the first of such institutes, Rothamsted Experimental Station, was started 150 years ago, there were few such specialists available, and the station's founder, John Bennet Lawes, had to develop a range of completely novel scientific methods to investigate the problems then confronting the British farmer. The magnitude of John Lawes' scientific foresight can be judged from the fact that most of his experimental techniques have never been improved and are now used in agricultural research throughout the world. Moreover, eight of the field experiments he initiated at Rothamsted, mainly between 1843 and 1856, persist with varying degrees of modification and continue to provide useful new information which he could never have envisaged. The most famous of Lawes' field experiments, the Broadbalk Experiment on the nutrition of winter wheat, was harvested for the one hundred and fiftieth time in 1993, and indeed qualifies as one of the (if not the) longest continuous experiments in the history of science.

Lawes' early life and background

John Lawes was born at Rothamsted Manor, near Harpenden, in 1814. His father died in 1822 and the family estate of nearly 250 acres (100 ha) was let to a tenant while John was sent to Eton and Brasenose College, Oxford. The tenant became insolvent, so the family moved back to Rothamsted in 1834, and at the age of 20 John took up management of the estate. He later wrote: 'At the age of 18 I went to Oxford where I remained 2 years learning little or nothing.' He did, however, attend some lectures on chemistry and these must have fired his enthusiasm, because 'much to mother's annoyance my first act after arrival at Rothamsted was to order one of the best bedrooms to be fitted up as a laboratory!'

In 1837 Lawes began pot experiments using manures supplying the elements known to occur in plants. He used animal charcoal as a manure and showed, as suggested by other early agricultural scientists, that its value was greatly increased if treated with sulphuric acid. Rock phosphates such as coprolites were treated in a similar way and the 'superphosphate of lime' thus prepared was found to be especially valuable for turnips. In 1840 and 1841 superphosphate made in a converted barn at Rothamsted was used on field crops on the estate and the results were so satisfactory that in 1842 Lawes took out a patent for its manufacture.

After his marriage on 28 December 1842, Lawes spent his honeymoon looking for a suitable site for his proposed fertiliser factory. 'Instead of a tour abroad I started one day in a boat on the Thames to find some waterside premises ... the loss of the proposed foreign tour was a great disappointment to my wife!' This midwinter search resulted in the purchase of a site beside Deptford Creek, which subsequently generated a small fortune from the sale of superphosphate to a very appreciative farming community. The work later expanded to another factory at Barking.

The partnership with Gilbert

On 1 June 1843, Lawes engaged Joseph Henry (later Sir Henry) Gilbert as a chemical assistant with the intention of starting large field experiments on the nutrition of the main arable crops grown at the time. Later he quoted this date as the foundation of Rothamsted Experimental Station.

Gilbert came from a very different background. Born at Kingston upon Hull in 1817, he was the son of a Congregational Minister and, according to his mother, had only three interests – electricity, arithmetic and chemistry. In 1838 he went to Glasgow University to study chemistry and botany, then moved to University College London in 1839 and finally to Giessen in Germany in 1840, to study with Liebig. Here he obtained a PhD within a few months, and then worked at University College and in Manchester before joining Lawes at Rothamsted.

Together Lawes and Gilbert directed the work of Rothamsted for 57 years, one of the longest scientific partnerships ever. Lawes was a naturally astute business man, quick to see the farmer's needs and provide practical advice based on the results of the Rothamsted experiments. By contrast, Gilbert lacked Lawes' vision but was a sound, meticulous scientist who ran the experiments with great care. Despite these differences, their skills were complementary and the partnership was very productive, leading to over 300 published papers and scientific letters. Both were elected fellows of The Royal Society; Lawes was made a baronet and Gilbert a knight.

Lawes financed the Rothamsted experiments from the profits of his factories and other business interests, which were sold for £300 000 in 1872. One-third of this fortune was used to set up the Lawes Agricultural Trust in 1889. This ensured continuation of the experiments and other scientific work, though since 1911 they have been supported increasingly from public funds.

The trust eventually acquired the whole of Rothamsted estate from the Lawes family in 1934, and subsequent purchases have increased the total area to 800 acres (300 ha). Land is thus available for new experiments on fields not occupied by the 'classical experiments', and the non-experimental areas are farmed commercially. Rothamsted Manor is now used as a residence for visiting scientists, though during World War II it housed a secret radio monitoring station, and was subsequently restored through generous contributions from numerous sources, including the Commonwealth countries.

Lawes died in 1900 and Gilbert in 1901. They were succeeded as directors of Rothamsted by A. D. Hall (1902–12), E. J. Russell (1912–43), W. G. Ogg (1943–58), F. C. Bawden (1958–72), L. Fowden (1973–86) and T. Lewis (1986–93).

The Broadbalk Experiment: continuous wheat and the need for soil nitrogen

This is quite the most famous of the Rothamsted classical experiments. Its original purpose was to see if 'mineral manures' (inorganic salts of phosphorus, potassium, sodium and magnesium in the proportions found in plant ash) were alone sufficient for good growth of wheat, or if addition of inorganic nitrogen (for example, as sodium nitrate or ammonium sulphate) to the soil is also required. Liebig[1] had argued that crops can obtain all the nitrogen they require from the atmosphere, but after only 3 years Lawes[2] had shown that nitrogen must be added for yields to match those on soil treated with farmyard manure, then widely used by farmers and the standard against which other treatments were compared. Liebig was unconvinced and increasingly criticised the Rothamsted experiments. This partly explains why the Broadbalk Experiment was continued long after its original purpose had been served – it was a living demonstration to scientists and farmers of the need for nitrogen from the soil and of the beneficial effects of inorganic fertilisers.

For the first few years the treatments of many of the 20 long narrow 0·24 ha plots of the Broadbalk Experiment varied, but in 1852 a more permanent scheme was established. The accumulating results continued to confirm the original conclusion that fertiliser nitrogen is of overriding importance to the successful production of winter wheat. So although Lawes' income came mainly from the sale of superphosphate, his scientific objectivity in partnership with Gilbert was such that he devoted much of his efforts to demonstrating at length, and beyond all reasonable doubt, the importance of nitrogen in crop nutrition.

In the early years the Broadbalk plots were ploughed by oxen (later by horses) and harvested with sickles by gangs of casual labour. After threshing, weights of grain and straw were recorded separately and samples were analysed. Unground samples were stored in sealed bottles or later in airtight tins. The soil of each plot was also sampled and analysed every 20 years or so and, like the crop samples, these have been stored to the present day. Broadbalk is now ploughed by tractor and harvested by combine harvester. When work was done by animals precautions were of course taken to avoid unplanned manuring. Buckets and spades were carried to collect dung, and at least one of the farm mares was successfully trained to hold her water until she reached the headland beyond the plots!

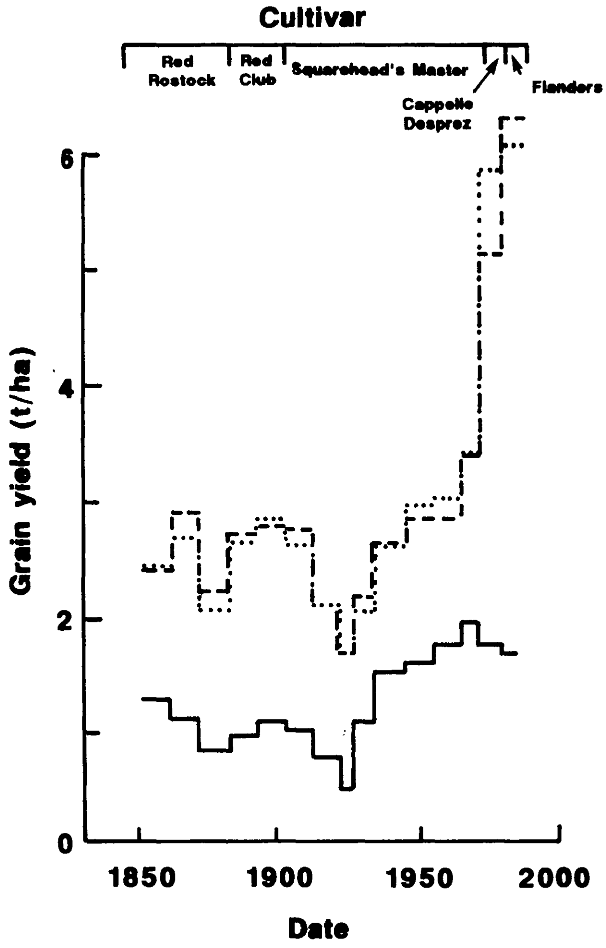
1 Aerial view of Broadbalk Winter Wheat Experiment showing long, narrow plots with different fertiliser treatments and sections at right angles for crop rotations and other treatments

Weeds were originally controlled by hand hoeing. By 1925 this had become impracticable, so strips or 'sections' crossing the plots at right angles (Fig. 1) were marked off and bare fallowed in rotation every fifth year to help control weeds and diseases. The five sections were increased to 10 in 1968, thus allowing new treatments to be introduced. Four remained in wheat: 0, 1 and 9 have grown wheat continuously since 1952, 1967 and 1959 respectively, using herbicides to control weeds, whereas section 8 receives no weedkillers and still needs occasional fallowing. To compare growth of continuous wheat with that after a 2 year break and after a bare fallow, two types of 3 year rotation were introduced: sections 2, 4 and 7 followed potatoes, spring beans, wheat, while sections 3, 5 and 6 followed a bare fallow, wheat, wheat rotation. These two rotations ran until 1979, when it was no longer possible to grow beans because of stem eelworm. Section 6 was then returned to continuous wheat but with no insecticide or fungicide treatments and sections 2, 3, 4, 5 and 7 went into a fallow, potatoes, wheat, wheat, wheat rotation. On section 0 chopped straw has been incorporated into the soil after harvest since 1986, and higher nitrogen rates (up to 288 kg/ha/year) were introduced on some plots in 1968 and 1985. The present complexity of the experiment is possible only because Lawes wisely decided to start with very large plots in 1843.

Yields of wheat in the Broadbalk Experiment

Until 1968 the best yields of wheat achieved with artificial fertilisers (35 kg P, 90 kg K, 35 kg Mg and at least 96 kg N per hectare) were similar to those given 35 t/ha farmyard manure (FYM), but after the introduction of the rotation and a change from long to short strawed varieties, FYM produced 0·5 t/ha more grain than fertilisers (Fig. 2). Once fungicides were introduced in 1979 the best yields from fertilisers (35 kg P, 90 kg K, 35 kg Mg and 192 kg N per hectare) exceeded those from FYM by nearly 2 t/ha, but were slightly less than those from 35 t/ha FYM + 96 kg N/ha (Fig. 3). Since 1968 wheat grown following the 2 year (fallow, potatoes) break has yielded 0·5–2·0 t/ha more than that grown continuously, because of the control of pathogens. Since 1985 even greater nitrogen application rates (up to 288 kg/ha) have been tested, but they have increased yields only slightly and only in continuous wheat.

Yields of grain of the long strawed varieties grown before 1968 (Red Rostock, Red Club and Squareheads Master) were much less than those of the short strawed varieties grown since (Cappelle Desprez, Flanders, Brimstone and Apollo). Between 1852 and 1967 the best grain yields were 2–3 t/ha, with a slight decline during World War I, when labour



— no manures; ... 35 t/ha/year farmyard manures; --- inorganic fertiliser (144 kg N, 35 kg P, 90 kg K, 35 kg Mg/ha/year)

2 **Mean decadal yields of Broadbalk plots receiving treatments indicated: varieties grown are shown above**

for hand weeding was scarce (Fig. 2); yields then recovered after regular fallowing was introduced. The yields of the nil (unfertilised) plot of Broadbalk remained fairly constant at 1·0–1·3 t/ha throughout the early decades of the experiment and have been slightly improved by fallowing (because nitrogen accumulates under fallow), use of herbicides and the 2 year break (Fig. 2). These levels are similar to the world average yield of wheat.

Although no nitrogen has been added to the nil plot for over 150 years, the crop on it removes about 30 kg N/ha/year from the soil, yet the total nitrogen content of the soil has changed little since 1865. Some nitrogen is supplied by free living, heterotrophic nitrogen fixing bacteria and blue–green algae and a little (3–4 kg/ha/year) is added in seed, but most is now known to be deposited from the atmosphere. Recent measurements[3] suggest that wet and dry deposition together supply a net total (i.e. after allowing for losses of nitrogen containing gases from soil and crop) of 40–45 kg N/ha/year to Broadbalk field, most of which originates from atmospheric pollution by industry and automobile exhaust fumes.

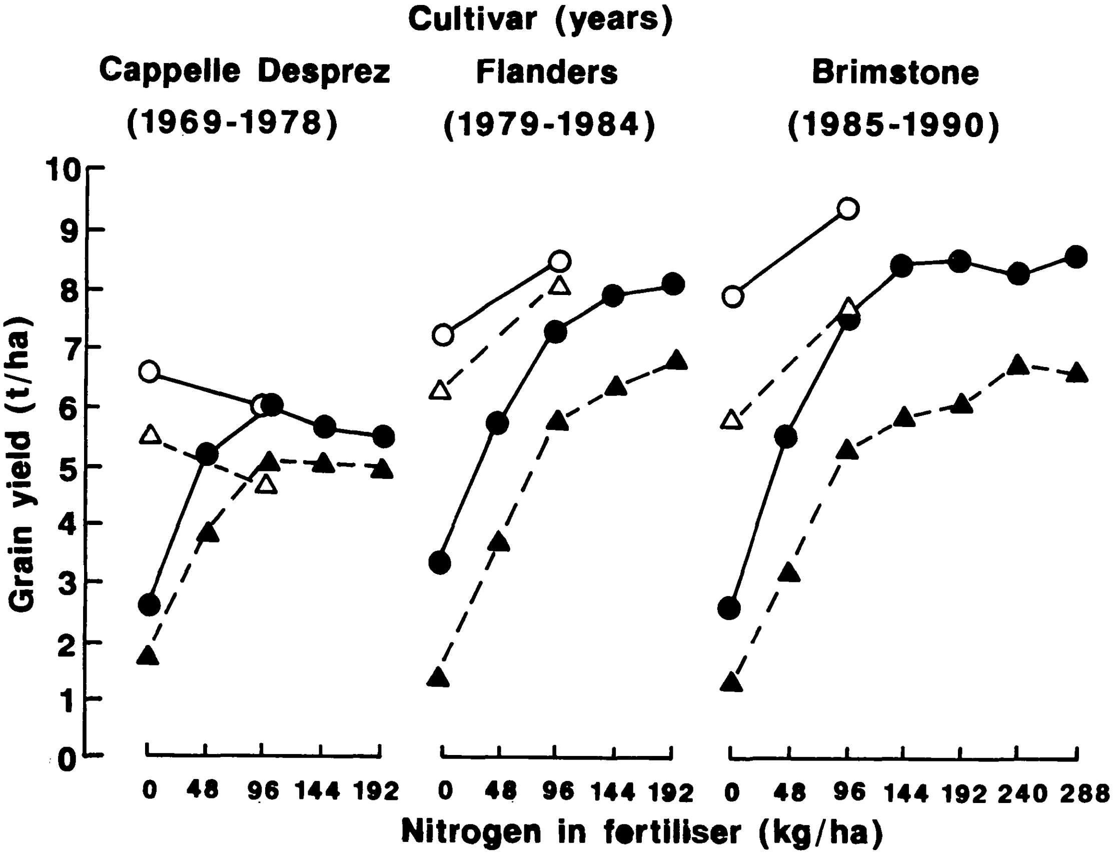
Soil organic matter on Broadbalk

The amounts of organic matter in the topsoil of Broadbalk plots not receiving FYM have remained steady since they were sampled in 1865, though plots receiving inorganic nitrogen have stabilised at slightly greater organic contents than the nil and minerals only plots. This is because the better fertilised crops leave more stubble and roots in the soil as well as giving greater yields of grain and straw. The annual dressings of 35 t FYM/ha have more than doubled the amounts of organic matter since 1865, and an equilibrium between inputs and losses has still not been achieved (Fig. 4).

The amounts of organic carbon in the stored soil samples collected at various times from Broadbalk and other Rothamsted 'classicals' provide a unique means of constructing and testing models for the turnover of organic matter in soil, that is the rate at which carbon taken from the atmosphere by plants and incorporated into soil is eventually returned to the atmosphere as carbon dioxide. From experiments on the decomposition of ^{14}C labelled plant material added to soil and from radiocarbon measurements of Rothamsted soil samples taken before and after atmospheric testing of thermonuclear devices had increased the ^{14}C content of organic matter entering the soil,[4] a six compartment model was developed by Rothamsted soil scientists to predict the effects of soil and crop management and weather on soil organic content.[5] The actual organic carbon contents and the model predictions based on these independent inputs for three Broadbalk plots with contrasting treatments are compared in Fig. 4. The agreement is good, the model satisfactorily predicting the consistent small difference in organic carbon between the nil and inorganically fertilised plots and the progressive increase on the FYM plot.

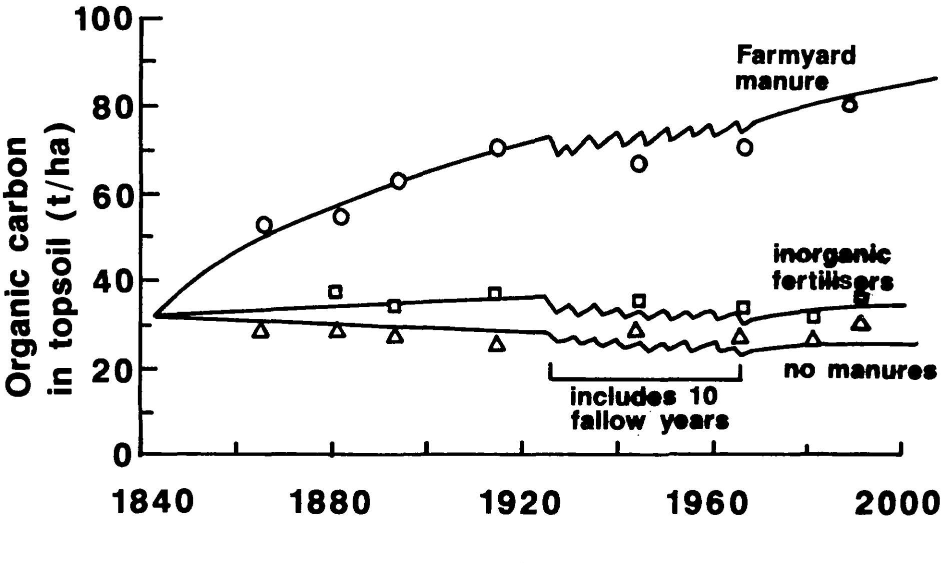
The fact that the Broadbalk plots with long continued inorganic fertiliser treatments have now reached steady state conditions in terms of organic matter content has also been used recently to study the cycling of nitrogen in soil growing winter wheat.[6] At a time when there is increasing environmental interest in leaching of nitrate to potable water reserves and of losses of nitrous oxide (a 'greenhouse' gas) to the atmosphere from arable soils, this work has greatly clarified the fate of inorganic nitrogenous fertiliser applied to winter wheat. From 1980 to 1983 the spring fertiliser applied to certain plots was labelled with ^{15}N, so that the extent to which the nitrogen was taken up by the crop or entered various organic components of the soil could be determined by mass spectrometry. At harvest less than 2% of the labelled nitrogen at any of the input rates (48–192 kg N/ha/year) remained in the soil as leachable nitrate. Larger amounts, about 20%, entered the soil microbial biomass and humus. On average, 60% was taken up by the crop and 20% was unaccounted for.

The steady state conditions allowed nitrogen balances to be drawn up for the inorganically fertilised



▲ continuous wheat; △ continuous wheat with farmyard manure; ● after 2 year break; ○ after 2 year break with farmyard manure

3 **Mean yields of grain on Broadbalk plots given farmyard manure and different amounts of nitrogen for three short strawed varieties grown since 1968**



△ no manures; □ inorganic fertilisers (144 kg N, 35 kg P, 90 kg K, 35 kg Mg/ha/year); ○ 35 t/ha/year farmyard manure

4 **Organic carbon contents of top 23 cm of soil from Broadbalk plots given treatments indicated: symbols show measured amounts and continuous lines amounts predicted from model of organic matter turnover**[5]

plots.[7] These showed that, in order to achieve a balance, it was necessary to include the 40–45 kg/ha/year input from the atmosphere and that an amount equivalent to approximately 30% of the total nitrogen inputs was lost each year by leaching of nitrate or by the denitrification processes that result in transfer of nitrous oxide and other gases to the atmosphere. Most of these losses occur during the winter, and since so little of the nitrogen applied as fertiliser in the spring remains unaltered in the soil at harvest, the nitrate and nitrous oxide must be derived mainly from decomposition (mineralisation) of soil organic matter and micro-organisms, not from unused fertiliser residues. Fertiliser nitrogen may influence nitrate leaching indirectly, because its use increases the microbial biomass and the larger crops it produces lead to greater crop residues in the soil,[8] both of which may later increase production of nitrate by winter mineralisation. However, the extra nitrate produced is much less than the amounts generated by ploughing up grassland or by use of organic manures.

Leaching losses from Broadbalk plots

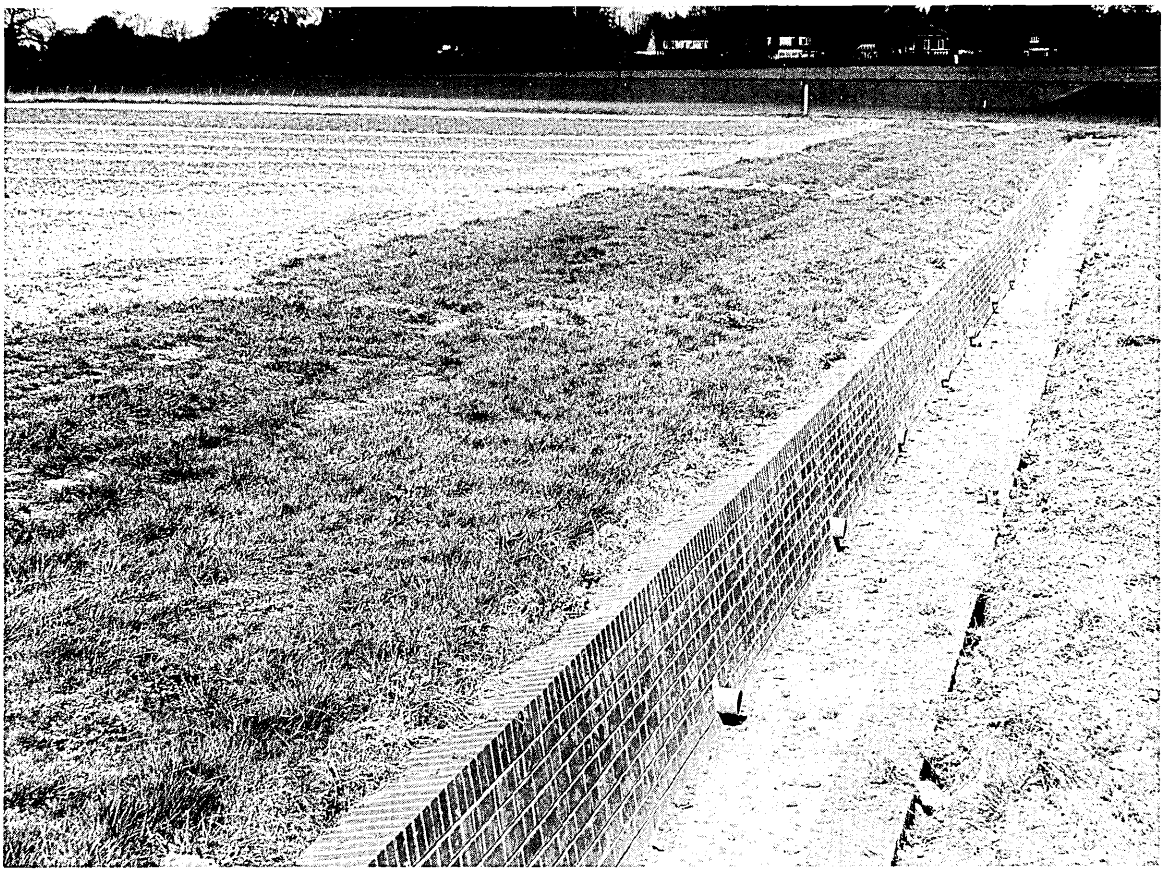
The ^{15}N method does not distinguish between nitrogen losses by leaching and denitrification; it gives only a total loss, calculated by difference. However, there are various methods of measuring leaching more directly.[3] One of the best was first developed by Lawes and Gilbert on Broadbalk. In 1849, 'horseshoe and sole' tile drains 5 cm in diameter were installed at 60 cm depth down the centres of 17 of the gently sloping plots. These were not originally intended for experimental purposes, merely to drain the soil in the manner then becoming popular on heavy clay land in Britain. However, in 1866 they were opened into small circular pits to allow the drainwater to be collected from each plot. Analyses of water samples collected on five occasions in 1866–68 indicated for the first time which nutrients were being lost by leaching from the plots.[9] The main losses were of nitrogen (as nitrate), calcium, chloride, sulphate and sodium; this was because most of the ammonium was converted to nitrate and the other nutrients added (phosphorus, potassium and magnesium) were all 'fixed' to soil minerals by adsorption or cation exchange, the latter process displacing mainly Ca^{2+} and Na^{+} ions.

Later drainwater samples collected up to 1881 confirmed these results and showed that the largest losses of nitrate were from plots given 144 kg N/ha, a greater amount than could be used by the crop variety grown at that time. Also drainflow from the FYM plot was less than from plots treated with inorganic fertilisers,[10] probably because the increase in soil organic matter from annual FYM applications had by then increased the water retaining capacity of the soil. Concentrations of nitrate in the winter drainwater samples were greatest on plots treated with nitrogenous manures (organic or inorganic) in the autumn. In spring samples they were greatest on plots receiving spring nitrogen as sodium nitrate, though ammonium sulphate without other nutrients also resulted in large nitrate losses because of the decreased ability of the crop to take up nitrate. Nitrogen supplied as ammonium or as an organic manure such as FYM must be transformed to nitrate before it can be taken up or leached, and the time taken by these processes can delay leaching losses compared with supplying nitrogen directly as nitrate. The main factors to be considered for minimising nitrate leaching are therefore:

- limiting the supply of nitrate to the crop to the period when it is most needed for rapid growth (spring and early summer)
- maintaining the water retaining capacity of the soil and limiting the flow of water through the profile, especially at times when the soil nitrate content is likely to be large
- ensuring good crop growth by applying the correct balance of nutrients and avoiding pest and disease damage.

Lawes and Gilbert were unable to calculate nitrogen balances for the Broadbalk plots in the same detail as recently achieved by the ^{15}N studies. This was mainly because the amounts of nitrate collected by the plot drains were only a small proportion of the total leaching losses, since much water passes down fissures in the clay subsoil between the drains and enters the Chalk aquifer at a depth of 2–5 m beneath the soil surface. The strongly fissured and permeable nature of the deep subsoil at Rothamsted results from a complex geological history of climatic change during the last 1–2 million years; freezing and deep frost disturbance occurred in glacial periods, alternating repeatedly with fairly intense chemical weathering under forest vegetation in warm interglacial periods.[11]

Although similar soils cover many chalk plateaux and some other upland surfaces in southern England, most British soils containing so much clay (50–60% $<2\ \mu m$) have not suffered these climatic vicissitudes and are consequently much less permeable. For example, the leaching experiment at Brimstone Farm, Oxfordshire, which is operated jointly by Rothamsted and ADAS Soil and Water Research Centre, Cambridge, is on a very impermeable soil (55% $<2\ \mu m$) over Oxford Clay, and loses little or no water below the depth of the plot drains.[12] Despite this hydrological difference, the nitrogen balance based on the Brimstone Experiment is similar in many respects to that for Broadbalk; for example, both show mean annual nitrogen losses by leaching and denitrification that are equal to or little more than the nitrogen inputs from non-fertiliser (mainly atmospheric) sources. This shows that with careful application of inorganic nitrogen fertilisers up to the optimum dressing for winter cereals (now about 175 kg/ha/year) there need be no more pollution of water supplies than under other arable land uses. In



5 Trench for collection of drainage water from plots of Broadbalk Winter Wheat Experiment, Section 9

the Brimstone Experiment the only cropping system or soil treatment that has resulted in significantly smaller leaching losses than winter cereals is unfertilised, ungrazed grass,[13] which is hardly a profitable farm crop.

In 1896 the Broadbalk soil drains were opened into a brick lined trench for ease of sampling, but little further research was done until quite recently. The drains are now being used to compare nitrate losses with those determined by a more recent, cheaper method of measuring leaching with porous ceramic suction cups inserted into the soil at different depths and also to determine the effects of long term fertiliser applications on winter leaching of nitrate produced by mineralisation of crop residues. As part of the sesquicentennial celebrations the trench has been rebuilt (Fig. 5) and section 9 redrained.

Studies of soil pollution on Broadbalk

The archive of soil and crop samples begun by Lawes and Gilbert has also proved useful for tracing the history of increasing soil pollution over the past 150 years. There is widespread concern in many countries that increases in soil cadmium levels resulting from atmospheric deposition, sewage sludge applications and use of phosphate fertilisers[14] may adversely affect human health because of increased uptake by crop plants.[15] Soil from the nil plot of Broadbalk shows an average increase since 1846 of 5·4 g Cd/ha/year, though most of the increase has occurred since 1920;[16] this must have come from atmospheric deposition, because the plot has never received sewage sludge or superphosphate. By contrast, the increase on a superphosphate treated plot since 1881 was only 2·6 g Cd/ha/year,[14] so the fertiliser applications (adding 2 g Cd/ha/year) have not caused any greater accumulation than that resulting from atmospheric deposition. This is probably because cadmium is retained by association with soil organic matter, which has increased very little on the plots treated with inorganic fertilisers. Grain samples from the plot given inorganic fertilisers showed a small, irregular increase in cadmium content over the past century.[17] However, grain from the FYM plot decreased in cadmium content, suggesting that organic matter retains cadmium to some extent against crop uptake as well as loss by leaching.

The Broadbalk soil and crop archive has also been used to study soil contamination by organic toxins such as polynuclear aromatic hydrocarbons (PAHs), a group of carcinogenic and mutagenic compounds formed by combustion of fossil fuels, plant materials (such as straw) and organic wastes. These aromatics are thought to be taken up from the soil by many crops, which, together with other dietary intakes, constitute the main exposure to PAHs for non-smokers. Over the past century the total PAH burden

6 Broadbalk Wilderness, setaside in 1882

of topsoil from the nil plot of Broadbalk has increased fivefold,[18] a value that must represent typical rural deposition rates in southern England; in most industrial and urban areas it would be greater than this. Some of the individual compounds (for example, benzofluoranthenes, benzopyrenes, pyrene and benzo(*a*)-anthracene) show much greater increases, up to thirtyfold, and actual inputs must have been even greater because some PAHs would have been lost by evaporation, oxidation, microbial degradation or translocation to subsoil horizons.[19] Amounts of PAHs in the archived grain samples from Broadbalk are very small and have declined over the past 60 years despite the increase in soil PAH content.[20] This suggests that there is little uptake from the soil. Any contamination of wheat grain probably occurs by direct deposition on the plant.

Broadbalk Wilderness

In 1882, about 0·2 ha of the previously cropped area of Broadbalk Field was enclosed by a fence and left unharvested and uncultivated, to see how effectively the wheat could compete with weeds. After 4 years the few surviving wheat plants were stunted, and none reappeared subsequently. Half of the area has remained untouched and is now woodland with ash, sycamore and oak trees, often more than 20 m high (Fig. 6), and a ground cover of dog's mercury, violet and blackberry with ivy in areas of densest shade. On the other half shrubs were hoed out annually to allow open vegetation to develop; this now consists of *inter alia* coarse grasses, hogweed, agrimony, willow herb, nettles, knapweed and cow parsley. Part of the open section adjacent to the woodland was mown several times annually from 1957 to 1960, and since then sheep have grazed this area. With mowing, the hogweed and cow parsley were replaced by ground ivy, but grasses did not increase substantially until grazing began. By 1962 perennial ryegrass and white clover had appeared, and subsequently ground ivy and other broadleaved plants have been progressively restricted.

On all parts of the Wilderness the soil rapidly gained organic matter; by 1964 the top 69 cm on the open section had gained 51 t/ha organic C and 4·5 t/ha N, which are more than the arable plot that has received 35 t FYM/ha/year since 1843. Since there were no legumes here, the gain of nitrogen (equivalent to 49 kg/ha/year) has come from the same sources as the nitrogen of the nil arable plot (wet and dry deposition, fixation by free living micro-organisms) and by bacterial activity in the rhizosphere of some of the perennial weeds, such as hogweed and ground ivy.

As a 'setaside experiment' now over a century old, Broadbalk Wilderness provides much useful information for predicting the ecological and environmental effects of the recent EU setaside regulations. For example, the long term importance of soil treatments preceding setaside is demonstrated by comparison of the soil properties of Broadbalk Wilderness (generously chalked when arable land before 1843) with those of a similar area nearby known as Geescroft Wilderness, which was setaside in 1885 on land that had previously been chalked less generously than Broadbalk Wilderness. From measurements on stored samples, the topsoil pH of Geescroft Wilderness declined from 7·1 in 1883 to 4·2 in 1983,[21] whereas that of Broadbalk Wilderness changed little over the same period; the latter soil still contains a little chalk. This may partly explain a much slower rate of organic matter accumulation in the soil of Geescroft Wilderness (approximately one-third the rate in Broadbalk Wilderness) and also explains botanical differences between the two. For example, the woodland of Geescroft Wilderness contains much more oak than that of Broadbalk Wilderness.

Other Rothamsted classical experiments

Lawes and Gilbert started long term experiments on most of the farm crops grown in their day. Those on potatoes, field beans, oats and red clover were discontinued in the nineteenth century, because yields became too small to justify continuing. They were unable to explain the failures, which probably resulted from pests and diseases that were uncontrolled in monoculture. A four course rotation experiment (Agdell) was started in 1848 and ended in 1990 and one on root crops from 1843 to 1968 (Barnfield) is now 'mothballed' in grass and clover. In addition to Broadbalk Winter Wheat and Broadbalk Wilderness, six others still survive: Geescroft Wilderness, Hoosfield Spring Barley, the Alternate Winter Wheat and Fallow, the Exhaustion Land, Park Grass Hay and the tiny Garden Clover Experiment. These together account for about 500 of the 5000 or so experimental plots currently in existence on Rothamsted Farm. Between them they have provided many useful principles applicable in agriculture, ecology and environmental science. In this context two are worth further comment – the Exhaustion Land, which illustrates the necessity for long term experiments in agriculture, and Park Grass, which was started as a field experiment on the nutrition of grass but soon developed into one of the most famous ecological experiments.

The Exhaustion Land Experiment arose from the need to put a cash value on the unexhausted residues of organic manures and fertilisers added to soil, for which an outgoing tenant farmer could be compensated in accordance with the terms of the Agricultural Holdings Act (1875). Lawes[22] and the Royal Agricultural Society of England[23] had disagreed over formulae for calculating compensation for the value of animal foodstuff residues and had therefore begun experiments in 1876 at Woburn Experimental Farm, Bedfordshire to settle the matter. However, problems had been encountered with the interpretation of results on the sandy soil at Woburn; in addition, the experiments there gave no data on inorganic fertiliser residues.

In 1901, A. D. Hall attempted to rectify this by modifying a Rothamsted experiment which had previously received variable annual dressings of nitrogen, phosphorus and potassium since 1856 and of FYM since 1876. Wheat had been grown from 1856 to 1876 and potatoes from 1877 to 1901. From 1902 to 1939 no nutrients were added and cereals were grown to measure the residual effects of the previous treatments. These were small in the absence of fresh nitrogen. From 1940 to 1991 spring barley was grown and nitrogen was applied annually, initially at a single rate (88 kg/ha), but from 1976 at four rates from 0 to 144 kg/ha. This nitrogen increased yields and allowed the crop to take advantage of phosphorus and potassium residues remaining in the soil from the 1856–1901 period. The effects of these residues were initially large, giving 2–3 t/ha more grain than where no phosphorus or potassium fertiliser or FYM had been applied before 1901, and even in the 1980s the difference was 0·9–1·7 t/ha, depending on nitrogen application rate. Thus, although provisional tables of compensation rates had been published much earlier,[24] it had taken over 80 years to assess fully the residual values of phosphorus and potassium added in inorganic and organic manures between 1856 and 1901. Recently half the experiment has been modified to measure the responses of barley (1986–1990) and wheat (since 1991) to fresh phosphorus (in the presence of adequate nitrogen and potassium supplies), to see how quickly the amounts of soil phosphorus can be built up to a level at which they no longer limit yield.

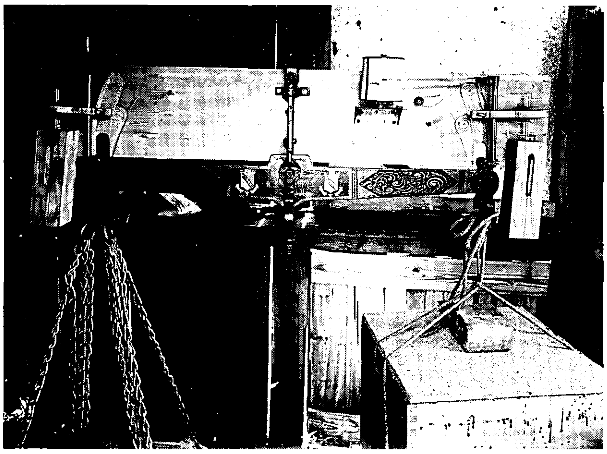
The Park Grass Hay Experiment was started in 1856, but had been pasture for at least a century before that. As on Broadbalk, there was originally a comparison between organic and inorganic fertilisers (here containing various combinations of phosphorus, potassium, sodium, magnesium, silicon and nitrogen supplied either as ammonium sulphate or as sodium nitrate) and a nil plot. The importance of 'minerals' for the yield of hay and its nutritional value was soon demonstrated, but by 1859 Lawes and Gilbert had noticed that the different combinations of nutrients were influencing the botanical composition of the sward.[25] The progressive changes were recorded by Gilbert, who trained local village boys to separate the numerous different plant species in the hay from each plot. The changes were most marked where applications of ammonium sulphate were increasing the soil acidity. Liming was tested in 1883 and 1887, but had little effect on yield or composition. From 1903 to 1964 burnt lime (later chalk) was applied every 4 years to half of each plot. Since 1965 the plots have been divided into four: one set of subplots remains unchalked and now has pH values ranging from 3·4 to 5·7, depending on fertiliser treatment; the other subplots receive chalk calculated to maintain pH values of 5·0, 6·0 and 7·0.

Recent mean annual yields of dry matter have ranged from 1·1 t/ha (pH 3·5, 48 kg N/ha as ammonium sulphate) to 8·0 t/ha (pH 7, 144 kg N/ha as ammonium sulphate, plus phosphorus, potassium, sodium, magnesium and silicon). On most plots yield decreases with decreasing pH. The unmanured plots have the most diverse plant assemblages (50–60 species equally distributed between grasses and dicotyledons) and include the legumes meadow vetchling and red clover, but yields are small.[26] Legumes are also abundant on plots receiving 'minerals' only. On the unlimed plots receiving ammonium sulphate the herbage is dominated by a limited range of acid tolerant grasses, but where lime is added there is a wider range of grasses and other species. Where nitrogen is supplied as sodium nitrate, there are at least 30 species present and liming has little effect on the herbage composition.

The original purpose of this experiment (to maximise yield) has long since been submerged by its ecological interest; it is in fact the longest running ecological field experiment anywhere.[27] Despite unchanging fertiliser treatments, the flora of many plots has changed slowly, often with periods of transient dominance by some species that were later displaced or leading to reduction of the original mixed flora to a monoculture. In addition, the abundance of some species is influenced by the cutting regime. Within species that are widely distributed on the different plots, such as sweet vernal grass, adaptation to the different pH and nutrient conditions has resulted in distinct populations with different morphological and physiological attributes. The differences are adaptive because they survive growth for several years in uniform conditions off the plots, so that when replanted they grow better in their own plots than in others.[28] In these and other ways[29] the Park Grass Experiment has provided unique evidence for testing various aspects of ecological theory. More practically, the results obtained have proved useful for management of amenity grassland; for example, many decorative wild species can be encouraged by avoiding application of certain nutrients and careful timing of mowing operations. However, the experiment also demonstrates that decorative meadows cannot be recreated simply by sowing wild seed mixtures into soil that has been enriched in nutrients by past fertiliser applications.

Rothamsted work on crop protection

Lawes and Gilbert's pioneering work on crop nutrition opened the way to large improvements in crop productivity throughout the world, but in turn allowed the expansion of insects and other organisms which could live on the crops. Some species became sufficiently numerous to be regarded as pests, competing with the farmer for the increased crop production. By the early twentieth century farmers were increasingly able to improve crop growth, but unable to protect the larger crops from pest and disease attack. This deficiency became especially apparent when great efforts were made to increase food production during World War I. As a result, Plant Pathology, Insecticides and Entomology Departments were founded at Rothamsted soon after the war ended. Initially there were attempts to deal with the urgent problem of 'wireworm' damage using tar oil extracts and later by application of specific compounds such as aromatic hydrocarbons and isothiocyanates.[30] However, the work rapidly broadened into a wide range of crop protection topics with an emphasis, as in the nutritional studies, on long term experimentation – an approach often facilitated by the stable framework of the classicals.



7 **Balance used for continuous recording of honeybee hives for 12 years at Rothamsted**

The rewards for continuous research effort over several decades are well illustrated by Rothamsted's search for better insecticides. In the 1930s the natural insecticidal properties of the *Pyrethrum* (now *Tanacetum*) daisy were studied and after World War II a research programme was started on the relationship between the chemical structure of pyrethroid compounds and their insecticidal activity. After 20 years this bore fruit with the isolation and identification of the active compounds and the demonstration of their unprecedented insecticidal power yet environmentally benign nature.[31] Continued work led to laboratory synthesis of a range of important artificial pyrethroids between 1968 and 1973; these are now produced commercially and in 1991 accounted for 18% of the world insecticide market ($1430m).

Soon after World War I work also began on beneficial insects, such as the honeybee. Production of honey by individual hives was monitored by continuous weighing for over 12 years[32] (Fig. 7). By the 1950s this work had extended to the role of chemical communication to control the activities of colonies, and through collaborative work with the National Institute of Medical Research the communicating chemical or pheromone regulating queen development, 9-oxodec-2-enoic acid, was identified.[33] Other bee pheromones have since been put to commercial use; for example, a synthetic version of one is used to attract escaping swarms into hives.[34]

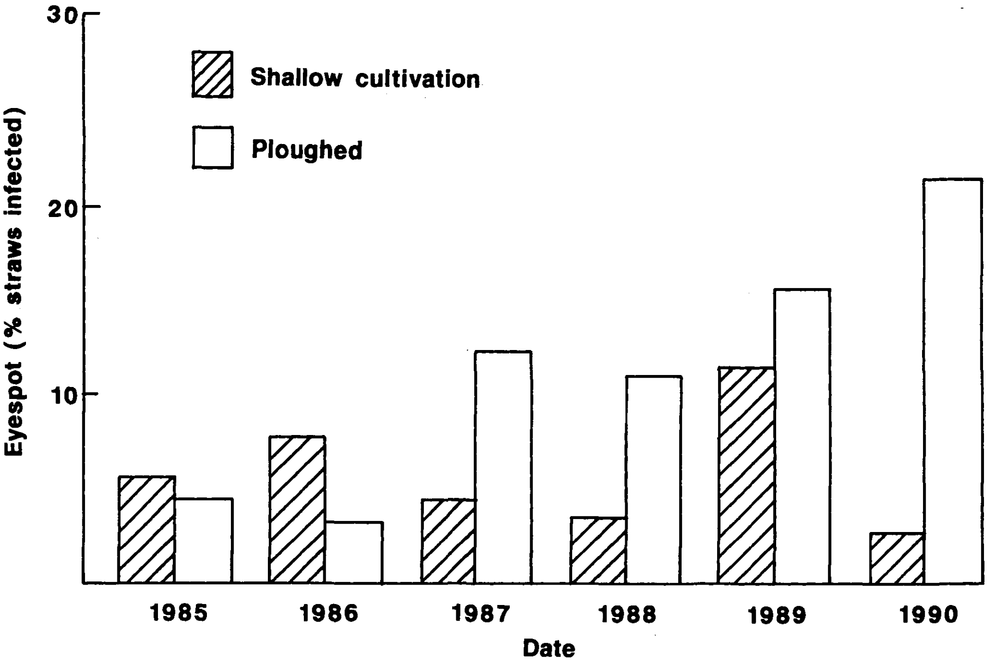
Early pesticides were of considerable help to the farmer, especially in the renewed drive to increase food production during World War II (Fig. 8).

8 Spraying of potatoes grown on Harpenden Common close to Rothamsted as part of drive for increased food production in World War II

However, they also damaged wildlife, so recent research at Rothamsted aims to decrease the amount of synthetic pesticides entering the environment. One strategy is to use pheromones to change insect behaviour and so decrease the damage they cause. A successful application of this approach was to use the synthetic sex attractant CDM to lure male pea moths (*Cydia nigricana*) to traps.[35] This allowed precise timing of the insecticidal sprays used to intercept egg laying females, thus increasing the insecticide's effectiveness and decreasing the number of applications required. More recently the oviposition pheromone of the malarial *Culex* mosquito has been synthesised[36] and used to attract female mosquitos to lay their eggs in pools treated with chemicals which kill the emerging larvae.[37] Also the sex pheromone isolated from the female damson hop aphid is being used to attract male aphids to lures where they are artificially infected with a pathogenic fungus.[38]

Another problem that has increased, or at least become more apparent, since intensification of agriculture in the early part of the present century, is the range of fungal, viral and other diseases attacking arable crops. The Plant Pathology Department has often made use of the more controlled conditions afforded by the classical experiments to study plant diseases and measure the effectiveness of control measures. In fact some diseases were first identified in these experiments; for example, the eyespot fungus (*Pseudocercosporella herpotrichoides*) was first recognised in Britain on the Broadbalk Winter Wheat Experiment in 1935. Eyespot and other soilborne fungal diseases of cereals, such as take-all (*Gaeumannomyces graminis* var. *tritici*), are a widespread problem in Britain and many other countries, and are impossible to control with fungicides because the volume of soil carrying the infection is so large.

One of the main advantages of the earlier practice of burning straw in the field after harvest was the partial control of many pests and diseases. Now this practice has been banned for environmental reasons, much more straw will be incorporated into the soil by ploughing and, as straw often carries eyespot, this disease is likely to increase. A large multidisciplinary field experiment testing straw incorporation was started in 1984. Work by Rothamsted plant pathologists compared the incidence of eyespot either where straw is ploughed in or where it is left on the surface and the subsequent crops are established by the cheaper method of shallow tine cultivation. In the first 2 years of the experiment there was less carryover of eyespot with ploughing. However, in the third year the position was reversed (Fig. 9) and the detrimental effect of ploughing then increased, probably because the repeated turnover of soil was returning more infected material to the surface. Had this experiment been terminated after 1 or 2 years an erroneous conclusion would have been reached. So, again, the long term experimental approach was vindicated; Lawes and Gilbert would surely have approved.



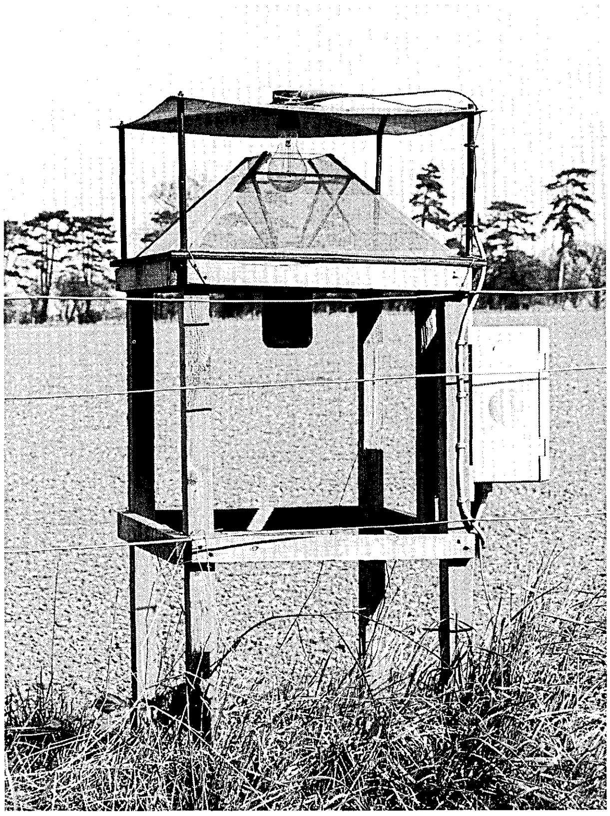
9 Effect of straw incorporation by ploughing on incidence of eyespot in winter wheat (reproduced with permission of J. F. Jenkyn and R. J. Gutteridge)

Ecological effects of environmental change

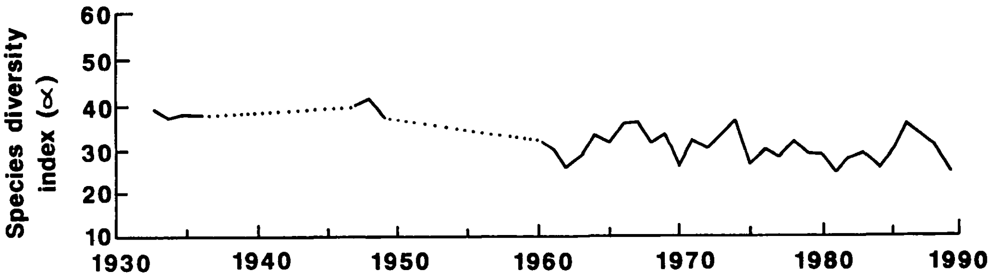
Many human activities result in pollution of the atmosphere or hydrosphere and are likely to influence plants and animals, but the effects are difficult to assess against a background of natural fluctuations in populations. Long term studies are necessary to distinguish man induced from natural variations, to understand the processes at work and to identify which human activities have disturbed the natural ecological balance.

Rothamsted is in an unrivalled position to conduct such studies. For example, in 1933 a light trap (Fig. 10) was placed at 1 m height beside the Barnfield Experiment to assess moth populations. Frequent observations to 1937, and again from 1946 to 1950, showed few changes attributable to human activities, but when the trap was re-established in 1960 it indicated a decrease in population diversity in the preceding decade (Fig. 11). This has been attributed to loss of habitats such as hedgerows, a decrease in food plant diversity through use of herbicides and increased use of insecticides. This change and the likely reasons for it could be discerned only because the database extended over several decades, albeit with some gaps. It would not have emerged over a period of even 10 years because of natural fluctuations in moth abundances.

The catch of the Barnfield light trap has been recorded daily since 1960, but despite large variations there has been no further long term decline in diversity (Fig. 11). A network of similar traps has been extended throughout Britain to monitor moth populations and to examine the role of migration in insect population dynamics. To extend the study to insects dispersed higher in the atmosphere, such as aphids, a 12·2 m high suction trap was established nearby in 1964 and a second network of these traps has now been extended to cover not only the whole of Britain but also 12 other European countries.



10 Rothamsted moth trap: number of moth species and total number of moths caught are recorded daily



11 Changes in species diversity of moths trapped at Rothamsted: decline in 1950s is probably related to post-war intensification of agriculture (reproduced with permission of I. P. Woiwod)

As these datasets lengthen, their value increases. Apart from the more obvious applications to monitoring and forecasting pest species, they are now emerging as unique resources for other ecological investigations, such as quantifying the impact of possible climatic change, a topic probably never envisaged by those who started the work in 1933.

Conclusions

Over the past 150 years research at Rothamsted Experimental Station has enabled food production in Britain and many other parts of the world to be increased so that, where the climate allows, it has kept pace with or even exceeded the requirements of an increasing human population. At the same time Rothamsted has provided solutions to many of the legal constraints and environmental problems confronting British farmers. The approach has been interdisciplinary, with conclusions drawn from long term monitoring of field experiments supported by laboratory or glasshouse work and tested by rigorous statistical methods. As a result the station has earned the worldwide respect of politicians and scientists from numerous disciplines for the reliability and objectivity of its conclusions and recommendations.

The capacity of human activities to bring about local or global environmental changes is increasing rapidly and forcing itself higher up national and international political agendas. As a result, the emphasis of Rothamsted's work has shifted in recent decades from agricultural production, so important during and immediately after World War II, to environmental problems thought to result from arable agriculture or likely to influence its effectiveness. In Britain modern intensive agriculture has been accused of causing a range of environmental problems from nitrate pollution of aquifers to the extinction of the Large Blue butterfly, though industrial and automobile pollution of air and water often seem at least equally worthy of blame. To resolve such problems we cannot force agriculture back into an inefficient, nineteenth century, pre-Lawes and Gilbert mould, as some idealists would wish. The need for efficient, intensive agriculture persists in an increasingly hungry world and the modern challenge to Rothamsted is to intensify it further but at the same time eliminate the environmental problems.

Before any environmental problem can be resolved we must first assess its true extent and cause. This is more likely to be achieved if there is already in existence a body of relevant, systematically collected data. The Rothamsted classicals and other long term databases have already provided the historical background needed to clarify these aspects of several current environmental problems, and more examples will certainly emerge in the future. However, long term monitoring is popular neither with 'snobbish experimental scientists'[39] nor with sponsors of scientific research, who will usually contemplate no financial commitment exceeding 3 years. Both need to understand that loyal continuity of scientific effort often brings far greater rewards than originally expected. After 50 years' work on the Rothamsted experiments Gilbert[40] wrote: 'Many of the experiments were commenced without any idea of long continuance .... It is, however, to long continuance that we owe some of the most interesting and the most valuable of our results.'

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Dr J.A. Catt
Rothamsted Experimental
Station
Harpenden
Herts. AL5 2JQ
UK

Dr John Catt was born in 1939 and trained as a geologist at Hull University, where he also completed his PhD in Quaternary geology. Since 1963 he has worked at Rothamsted Experimental Station, studying the mineralogy and genesis of English soils, the effects of Quaternary climatic change on soil properties and the effects of soil variation on crop growth and yield. Recently he has worked on environmental impacts of agriculture, such as contamination of surface waters through losses of nitrate, phosphate and pesticides by leaching, surface runoff and soil erosion. He has written more than 130 research papers on these subjects and two textbooks on applications of Quaternary geology to soil mapping and soil properties. From 1988 to 1990 he held an administrative post as assistant to the Director of Rothamsted. He is currently Editor of *Soil Use and Management*, Honorary Research Fellow in Geography at University College London, Visiting Professor of Geography at Birkbeck College London and Visiting Professor of Soil Science and Geology at Prague Agricultural University.

Dr I. F. Henderson
Rothamsted Experimental
Station
Harpenden
Herts. AL5 2JQ
UK

Dr Ian Henderson is a biologist specialising in the control of damage to crops by insects and other invertebrate pests. After graduating from Glasgow University he travelled extensively, studying and collecting beneficial insects for international biological control programmes. He subsequently took root at Rothamsted Experimental Station and considers himself fortunate to have spent the bulk of his scientific career there, surrounded by original minds and agricultural tradition.