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Woburn Experimental Farm

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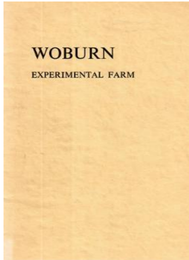

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WOBURN

EXPERIMENTAL FARM

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WOBURN

EXPERIMENTAL FARM

A Hundred Years of Agricultural Research Devoted to Improving the Productivity of Light Land

A. E. JOHNSTON

Published July 1977
to Commemorate the
Centenary of the First
Harvest in 1877

LAWES AGRICULTURAL TRUST

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Rothamsted Experimental Station,
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DR. J. C. A. VOELCKER,
1822–84

DR. J. A. VOELCKER,
1854–1937

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Woburn Experimental Farm

History

The agricultural background

Woburn Experimental Farm owes its existence to the Agricultural Holdings Act (England) 1875 which affected some of the relations between landlord and tenant. The need for this legislation arose gradually during the eighteenth and early nineteenth centuries as progressive tenant farmers sought to improve the productivity of their holdings. Such farmers soon found that increased productivity could only be achieved if money was spent on new and improved buildings, fences, draining, marling and chalking and on the purchase of extra feedingstuffs for their stock and manures for their crops. Tenant farmers were deterred from making such improvements because the existing laws of agricultural tenures gave no security for any capital invested. However, in various parts of the country, notably Lincolnshire, customs had arisen whereby landlords compensated tenants leaving their holdings for the value of any unexhausted improvements.

The value of this custom, often known as the 'custom of the country', was appreciated by Philip Pusey (1799–1855). The Pusey estates extended to about 5000 acres (2025 ha) in Berkshire and Philip Pusey was a founder member in 1838 of the English Agricultural Society which in 1840 became the Royal Agricultural Society of England (RASE). He was President of the Society in 1840–41 and again in 1853–54 and the first Chairman of the Society's Journal Committee and the effective editor of the Journal until 1855. Many of his articles and editorial comments show that Pusey was an advocate of 'Farmers Tenant Right'. He first introduced the term 'tenant right' in the House of Commons in the late 1840s after bills designed to give an agricultural tenant compensation for unexhausted improvements had been introduced without success in the House of Lords in the early 1840s. Pusey saw that, partly as a result of the Napoleonic Wars, there had for long been too little capital invested in agriculture. His remedy was to encourage tenant farmers to invest their own money and he saw the Lincolnshire Covenants as a way of financially compensating a tenant for any improvement, the benefit of which could not have been fully realised when he gave up the tenancy. The report of Pusey's Agricultural Customs Committee (1848) formed the basis of subsequent legislation on tenant right, first in the Landlord and Tenant Act of 1851, which gave only a few rights to the tenant, and then in the much more comprehensive Agricultural Holdings Act (England) 1875.

The 1875 Act was preceded by the Irish Land Act of 1870 which awarded compensation to an outgoing tenant for 'tillages, manures and other like farming works, the benefit of which is unexhausted at the time of the tenant quitting his holding'. If landlord and tenant could not agree on the compensation then arbitration was necessary and J. B. Lawes of Rothamsted was called as a scientific witness in one such case. This experience led him to comment that 'the Act is very explicit in all that related to the legal machinery

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by which claims may be tried or established; but it gives no information as to what constitutes unexhausted value, or how that value is to be estimated'. Pusey's Committee report shows that most local customs awarded compensation based on cost, but as early as 1862 Lawes thought this had little merit for purchased feedingstuffs given to animals.

Lawes and his co-worker Gilbert are now best remembered for their experiments on crops but they also did work on animal feeding at Rothamsted. They showed that only a small proportion of *plant nutrients* (N, P and K) in feedingstuffs were retained in the increased bodyweight of fattening stock or removed from the farm in dairy produce. The excess was in the dung and urine. Lawes and Gilbert estimated the amounts of N, P and K excreted by stock when they consumed a ton of each feedingstuff. The cost of buying these amounts of N, P and K at the current prices of purchased manures was calculated and called the original manure value of the feedingstuff. In 1875 Lawes published his first table of such values which, in some cases, bore little relation to the cost of the feedingstuff. Foods rich in carbohydrate or oil, highly esteemed for feeding to fattening stock, were costly but the dung produced contained little N, P and K. For example, in 1876 the purchase price per ton of linseed cake, decorticated cotton cake and barley meal was £12.50, £10.00 and £9.25 respectively; Lawes calculated their original manure values to be £4.62, £6.50 and £1.10.

Thus Lawes and Gilbert provided experimental evidence for paying compensation for purchased feedingstuffs and showed that this should be on the basis of manure value and not initial cost. In 1875 Lawes also pointed out that deductions should be made from the original manure value not only for losses, especially of N, that occurred in making manure but also for the number of crops grown after its application to the land. He tentatively suggested a 20% decrease for losses and writing off the manurial effect over three years.

The 1875 Act divided improvements which might be undertaken by a tenant into three classes.

Class 1 included drainage of land, erection or enlargement of buildings, laying down permanent pasture, making roads, bridges, fences.

Class 2 included chalking of land, clay burning, claying, liming and marling of land.

Class 3 was (1) application to land of purchased artificial or other purchased manures.
(2) consumption on the holding by cattle, sheep or pigs of cake or other feedingstuff not produced on the holding.

It was suggested that unexhausted values for improvements in class 3 would probably be written off over a period not exceeding two years and would not be payable if applied for a crop of corn, potatoes, hay or seeds or other exhausting crop. The small amounts of purchased artificial manures used at that time were probably applied to exhaustive crops and so were automatically excluded from claims for compensation. The restrictive clause did not appear in the 1883 Act, which repealed all existing Acts, but it is unlikely that this led immediately to a large number of claims. However, as fertiliser use increased, claims became more numerous and in the early years of this century the Central Association of Agricultural and Tenant-Right Valuers asked Voelcker and Hall if they could produce a table of compensation for artificial manures.

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Voelcker and Hall's table, which was headed 'From such data as are available the following Scale of Compensation may be taken as some guide', was first published in 1913; it included a range of artificial manures, fertilisers and lime.

Thus the 1875 Act gave a tenant the right to compensation but the amount had to be settled by agreement or arbitration. The manurial value of feedingstuffs became a much debated topic, not least within the RASE, because landlords and tenants wished to know if Lawes's tables could be relied on. Early in 1876 Dr J. C. A. Voelcker, Consulting Chemist to the RASE (p. 6), published a paper supporting Lawes's calculation of manurial values but suggested that the deduction for losses of N should be much nearer 50% rather than Lawes's 20% (Voelcker, 1876).

The RASE and the Duke of Bedford

At an RASE Council Meeting in November 1875, Mr C. Randell stressed the desirability of settling the matter of manurial values by direct experiments on different soils and under different conditions. The matter was referred to the Chemical Committee of the RASE; they acted with praiseworthy speed. In February 1876 they heard statements from scientific witnesses, Lawes and Voelcker amongst them, and from various 'practical' men, farmers and valuers. The Committee reported to Council in April that there was general support for Lawes's table but they stressed the need for supporting experimental evidence. It was suggested that this might be got by ordinary farmers making experiments in the course of their farm practice but the majority view was that these experiments would not be sufficiently accurate for the results to command confidence. At the same time there were few people with the necessary expertise to make field experiments.

The situation was resolved, as so often, by a compromise. The then Duke of Bedford (Hastings Russell, the 9th Duke), who was a Vice-President of the RASE, was aware of the value of experiments; records show that from as early as 1811 experiments with various manures had been made at Woburn. The Duke offered the RASE possession of a farm on the Woburn Estate and money to pay for experiments if the Society would be responsible for them and for the management of the farm. The offer was accepted, the Chemical Committee, renamed the Chemical and Woburn Committee, were made responsible and Lawes and Voelcker were asked to design suitable experiments.

Crawley Mill Farm, Husborne Crawley, with a granary and brick-kiln ground (now the large lake near the farm buildings) was selected. Letters in Estate archives suggest that the outgoing tenant requested what was considered to be excessive compensation for loss of tenancy and tenant right.

However no single field on the farm was large enough to make the proposed experiment on the manurial value of different feedingstuffs. The Duke therefore arranged to rent Stackyard Field from the tenant of Birchmore Farm. Although a mile from Crawley Mill Farm this was the only suitable field in the district. The original arrangement was for the Duke to pay £2 per acre each year for seven years but the tenant died during this period and the Estate apparently took the opportunity of adding Stackyard Field to Crawley Mill Farm.

Correspondence in the archives shows that nearly all the preliminary arrangements with the Duke's agent were made by Lawes. The Chemical

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Committee of the RASE became tenants at will of Crawley Mill Farm and Stackyard Field from Michaelmas 1876 at an agreed rent, paid to the Estate, which was about average for the class of land. The farm then consisted of 90 acres (36 ha) of which 67 acres were arable and 23 grass; Stackyard Field was just over 26 acres (10·5 ha). The acreage was increased again, at Michaelmas 1879, when Warren Field (about 14 acres) was made available for experiments on soluble and insoluble P fertilisers applied to arable crops. The account of this experiment shows that steam tackle was used for the preliminary cultivation of this heavy land. There were no buildings at the farm suitable for animal feeding experiments but during 1876 a building containing eight feeding boxes, each with cemented floor and rendered walls to prevent seepage, was built at the Duke's expense. In addition a weighbridge was installed. The first feeding experiments were made during the winter of 1876–77. The feeding boxes have only recently been demolished to make way for a potato store.

The accounts show that requests to the Duke for money were always met promptly. The 10th Duke continued to support the farm and so did the 11th Duke until 1912; the reasons for withdrawing are given later (p. 8). The cost to successive Dukes of Bedford was about £600 a year during the period 1876–1912.

The opportunity for making experiments on the light sandy loam soil at Woburn led Lawes and Voelcker to propose not only an experiment on the manurial value of different animal feedingstuffs but also experiments on the continuous growing of both winter wheat and spring barley. There was much discussion at that time whether Lawes and Gilbert's success in growing corn crops continuously on the heavier clay loam soils at Rothamsted could be repeated on light land. Today many farmers enjoy freedom of cropping and husbandry not allowed to the tenant farmer of the 1870s. Then the tenancy agreement often dictated the rotation to be followed and restricted what could be sold off the farm. There is a copy of a letter in the Woburn archives which refused a tenant permission to take a second successive cereal crop after a crop of sainfoin.

The first crops of wheat and barley were harvested in 1877 and in that year the feeding experiment was started on half of the 16 acres it was to occupy. Lawes and Voelcker reported the results in detail in the RASE Journal in 1878, the only report signed by both of them. Lawes seems to have resented interference by the Woburn Committee which had appointed a Mr Cathcart to superintend the experiments under the direction of Lawes. Cathcart was apparently censured for devoting too much effort to the experiments on Stackyard and not enough to making a commercial success of the rest of the farm, which was in a poor condition when taken over. Cathcart left to become Professor of Agriculture at Cirencester and Voelcker assumed responsibility for the experimental programme. Although both Lawes and Gilbert continued their interest in the results from Woburn, neither became personally involved again.

The Voelckers, father and son

Dr J. C. Augustus Voelcker (1822–84) was born in Germany, studied chemistry at Göttingen and worked for a short while with Liebig at Giessen and in Holland. In 1847 he was persuaded to go to the Agricultural Chemistry

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Association of Scotland's laboratory in Edinburgh, where he was both analyst and consulting chemist. He was appointed Professor of Chemistry at the Royal Agricultural College, Cirencester in 1849 and Consulting Chemist to the RASE in 1857. During 1857–62 he retained his Professorship at Cirencester and this gave him the opportunity to make field experiments there whilst the associated laboratory work was done in London. In this period he studied both the effects of storage on the composition of farmyard manure (FYM) and the capacity of soils to absorb ammonia, potassium and sodium. During the early 1860s he worked extensively on milk and dairy products. One of his major analytical studies was on the composition of drainage waters from soils given different manurial treatments on Broadbalk at Rothamsted. These analyses established that nitrate, sulphate, chloride, calcium and magnesium were lost in land drainage but that phosphorus and potassium were largely retained by the clay loam soil.

As Consulting Chemist to the RASE he analysed purchased feedingstuffs and manures for members. His reports, often exposing cases of adulteration or poor value for money, were published in the Society's Journal and so did much to raise the standard of materials offered for sale. He also had his own laboratories and did consultancy work. Voelcker and Gilbert were both extremely competent analysts and well acquainted professionally.

When Voelcker died in 1884 his son, John Augustus, succeeded him both as Consultant Chemist to the RASE and as Director of the Woburn Farm. J. A. Voelcker (1854–1937) graduated from University College, London and then studied for his Ph.D. at Giessen. He too quickly gained a reputation as an analyst and was at one time President of the Society of Public Analysts. He represented the interests of the RASE on many occasions. Not least of these was the various revisions (with A. D. Hall) of Lawes and Gilbert's tables (1897, 1898) of manurial values of feedingstuffs and the introduction, already mentioned, of the first table setting out residual values for artificial fertilisers and lime (Voelcker and Hall, 1902, 1913).

The Hills Bequest

Between 1877 and the late 1890s all samples taken from experiments at Woburn had to be analysed at the Society's London laboratory. Then in 1896 the RASE accepted a bequest of £10 000 from Mr E. H. Hills, a member of a firm of chemical manufacturers and makers of artificial manures, who also farmed in Sussex. He wanted the RASE to make experiments on the value of the 'rarer forms of ash' (trace elements) for agricultural crops. It was decided that this could be done best by pot culture techniques currently being developed in Germany. Buildings for a Pot-Culture Station, the first to be built in this country, were started at Woburn in April 1897 and completed early in 1898 (Voelcker, 1900). They consisted of a laboratory for analytical work, with office and store room, a large glasshouse and an area enclosed by small mesh wire netting supported on a metal frame, 'the cage'. The zinc or glazed earthenware pots in which the experimental crops were grown stood on trucks which could be moved between glasshouse and cage on rails. The laboratory building, now converted to offices, still stands; the glasshouse, much modified, is used as a workroom but the cage and railway have been dismantled.

A resident research chemist was appointed to make laboratory and glass-

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house experiments and take meterological observations with instruments first installed in 1898. The chemist was responsible to Voelcker and in 1898 H. H. Mann (1872–1961) was appointed. He was only there a short time when he accepted an appointment in India in 1900. However, when he retired from India in 1928 after a distinguished career in tea research and agricultural education, Mann returned to Woburn and worked there until 1956.

The Development Commission

Changes in financing Woburn came at a time of increasing costs and general uncertainty. Late in 1909 the Development Act, which set up the Development Commission, was passed. Substantially the Act was in two parts. One part provided for the 'economic development of the United Kingdom' and appeared mainly as a scheme to stimulate production from the land. There were two important features; firstly the Commission was permanent and the number of members and their tenure of office were fixed by law. The Commissioners were therefore not readily amenable to pressure from outside sources. Secondly, money was provided by Parliament in advance of any plans for its expenditure; for the first five years up to March 1915 the Commission was given £2·9 million pounds. A. D. Hall (Director of Rothamsted, 1902–12) was appointed an unpaid Commissioner at the outset, and a full-time Commissioner-with-Salary in 1912. Schemes for improving both research and education in agriculture were implemented under his guidance.

Once such funds were available the 11th Duke of Bedford decided to withdraw his financial support for the Woburn Farm. In December 1911 representatives of the RASE met the President of the Board of Agriculture (later to become the Ministry) and the Commissioners to try to secure a grant for Woburn. The application was successful and £500 was given for 1912–13; subsequently this grant was renewed each year. Apparently the Board of Agriculture would have liked to see the work at Woburn expanded. One suggestion was for the appointment of a plant physiologist to work on problems suggested by results from the pot experiments. However, neither the Board nor the Development Commission were able to increase their financial support and the RASE was unwilling to extend its commitment.

About this time there was much discussion within the RASE whether or not to continue the Woburn experiments. There was a long debate in Council in 1915 when the Chemical and Woburn Committee were successful in persuading Council to keep Woburn. It now seems almost unbelievable that an annual expenditure by the Society of about £150 was the cause of so much concern when gross annual income was about £10 000 and reserve funds exceeded £70 000.

Changes in the tenancy

A large financial loss on the Royal Show at Darlington in 1920 caused Woburn's future to be discussed again. An adroitly worded motion by the Finance Committee succeeded in getting the financial affairs of the Society, including those of Woburn, considered by a Special Committee. In addition, this Committee was given the power to terminate the tenancy of Crawley Mill Farm if this was thought to be financially desirable. The Committee gave the Duke of Bedford notice of intent to terminate the tenancy and then presented their report to Council at the end of 1920. Their recommendations

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effectively linked possibilities for increasing revenue from the Royal Show with saving money by giving up Woburn. The report was debated at great length and with much acrimony. The Council Chairman was given no opportunity to rationalise the situation by separating the two issues and the report was passed. When Council passed the report they automatically confirmed the notice to quit the tenancy at Michaelmas 1921.

Voelcker as tenant. Voelcker, however, had decided that he would continue the experiments and arranged to take the tenancy of the farm from October 1921. The RASE offered the crop and soil samples collected during 1876–1920 to Rothamsted, the offer was accepted and it was agreed with Voelcker that the samples would remain at Woburn; most are still there. The work done under the Hills Bequest was transferred to the Agriculture Department at Cambridge University, but the buildings and equipment were left at Woburn for Voelcker's use. The live and dead stock on the farm were not transferred. Their sale in September 1921 realised £635.

The RASE had one further role to play regarding Woburn. In February 1922 the Chemical Committee appointed a sub-committee 'to consider in what way—in view of the altered circumstances—the scientific side of the Society might be developed'. As a result of their report a Research Committee was established. Money from their Research Fund subsequently paid for work to be done at Rothamsted (from 1929) on analysing Woburn data using R. A. Fisher's statistical methods. In addition they suggested that all experimental work so far undertaken by the RASE, both at Woburn and on commercial farms, should be summarised and published. This suggestion was realised, at least in part, with the publication in 1936 of Russell and Voelcker's book, *Fifty Years of Field Experiments at the Woburn Experimental Station.*

In 1921 the Ministry of Agriculture decided to continue the annual grant of £500 towards the cost of the experiments which were mainly in Stackyard and Lansome fields. The grant was conditional on some supervision and this was to be exercised by Rothamsted's Governing Body, the Lawes Agricultural Trust (LAT); the grant was paid through Rothamsted. The experiments and farm were run by Voelcker for five years until increasing costs forced him to give up. The LAT then decided to take over and the Trustees took the tenancy of the farm in October 1926. Keeping Woburn cost Voelcker just under £2000. It is no exaggeration to say that those who, in recent years, have enhanced their scientific reputations by work done at Woburn owe much to him. If he had not taken the tenancy in 1921 the farm would have been lost to agricultural research.

Rothamsted assumes responsibility

From 1926 to 1936 the Rothamsted Farm Manager was responsible for all farming operations at Woburn. Voelcker, who was still Consulting Chemist to the RASE and working in London, was Honorary Local Director and from 1928 Mann supervised the field experiments and laboratory work. T. W. Barnes (1901–74) was appointed as chemist in 1928. Laboratory facilities were, however, far from satisfactory, and Barnes' work was restricted mainly to nitrogen analyses of crops and soils especially those from the Green Manuring, Market Garden and Ley Arable experiments. Later he undertook much daily supervision of the Irrigation experiment and investigated in detail

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the fate of N applied to grass plots with and without irrigation. When he retired in 1966 his vacancy was not filled.

Charity Farm. Both Mann and Barnes did much for the Husborne Crawley Charity Trustees; the Woburn staff are still involved for A. W. Neill, Farm Bailiff at Woburn, is Treasurer to the Trustees. The Trustees own Charity Farm, Husborne Crawley. Most of this farm, originally about 55 acres, is on heavy soil and was in permanent grass when in 1907 the tenancy was taken by the RASE. The Society first conducted an inquiry into tuberculosis in cattle, 1907–11, and built extra huts and pens so that stock could be kept in isolation. Later, 1912–18, a series of calf-rearing experiments were made there. In 1921 the RASE gave up the tenancy not only of Crawley Mill Farm but also of Charity Farm. Voelcker did not take the tenancy of Charity Farm.

The Farm today

Voelcker retired from his honorary directorship in 1936 and Mann assumed sole charge, not only for the experiments but also for the farm, being responsible to the Director at Rothamsted until 1946. In 1946 the Head of Farms at Rothamsted was again made responsible for all farming operations. Mann, however, continued to work on field and glasshouse experiments until he officially retired in 1956. From 1957 to 1968 C. A. Thorold assumed Mann's responsibilities but when he retired the vacancy was not filled.

Even in the 1930s laboratory facilities at Woburn were less than adequate and after the Second World War there was little desire to expand them. In the 1950s the increasing availability of road transport and later the opening of the M1 motorway eased travel between Rothamsted and Woburn and gradually all laboratory work was transferred to Harpenden. Currently the field experiments at Woburn, like those at Rothamsted, are the responsibility of the Field Plots Committee. By the mid-1960s the experimental programme at Woburn had increased so much that there were too few suitable sites. At Michaelmas 1962 the Woburn Estate were able to offer the tenancy of The Dairy Farm (17·5 ha) Husborne Crawley, and later two other fields were made available. These were Horsepool Lane Close, 3·3 ha, (1971) and Far Field 3·6 ha (1972).

Today the Woburn Experimental Farm is approximately 77 ha (190 acres). At Woburn the permanent staff consists of a bailiff, responsible to the Head of Farms for day to day management, two recorders who make experimental and meteorological observations and three farm workers. Some specialist help is provided by staff from Rothamsted and sponsors of experiments visit to make observations and take soil and mid-season crop samples, harvest time samples being taken by the Woburn staff.

In retrospect

In retrospect it is probably not unfair to say that the period from the First World War to the early 1950s was one of 'care and maintenance'. The rotation and green manuring experiments had not given the results confidently expected of them, the continuous growing of wheat and barley had run into serious problems and results from experiments in Lansome Field were very variable. These problems could not be adequately investigated because lack of money made expansion at Woburn impossible. Staff at Rothamsted did as much as possible but most were fully committed to other research projects.

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In 1931 a six-course rotation experiment was started on both farms. During the war there was considerable interest in increasing the productivity of light soils and the Market Garden experiment, 1942–67, measured the effects of large dressings of bulky organic manures. Probably however the experiment which, more than any other, served to reawaken interest at Woburn was the Ley Arable experiment started in 1938. This was the first experiment in this country to test one of the very few aspects of ley farming amenable to field experimentation, namely the extent to which leys can increase the yield of subsequent arable crops. As resources at Rothamsted increased both the Chemistry and Nematology Departments were able to investigate problems which became obvious during the 1950s. From these investigations the work of both Departments and others gradually expanded at Woburn.

During the discussion in the 1920s on the future of Woburn one member of the RASE contended that there was no point in continuing as the land was unfit for agriculture being altogether too light. The achievement of the last 20 years has been the large increase in yields of most crops at Woburn. It was in the Ley Arable experiment in 1971 that potatoes first yielded more than 75 t ha^{-1} (30 tons/acre) when biocides (chloropicrin and aldicarb) were used with large dressings of fertilisers.

The next two sections describe some of the work done at Woburn in the early years and that done since the 1950s.

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Early Experiments

Experiments on the unexhausted manure value of animal feedingstuffs, the Rotation experiments

This experiment benefited from experience gained by Lawes and Gilbert at Rothamsted. In 1848 they started the Agdell Rotation experiment, which tested fertilisers, but only one crop was grown each year and the plots, though large by present standards, could not be easily subdivided to compare carting off the produce with consuming it on the plots by stock, 'feeding-off'.

The treatments and design of the Woburn experiment are given in detail because they illustrate the careful planning given to it. There were four treatments, two manures and two fertilisers. The manures were got by feeding decorticated cotton cake (6·9% N) or maize meal (1·7% N); in 1876 the estimated money value of the manure from one ton of each feed was £6.50 and £1.55, respectively. The fertilisers tested supplied NPKMg equivalent to the amounts estimated to be in the manure from the two feeds. The feeding-stuffs were used in two ways. They were given as supplementary feed to sheep grazing the clover swards and they were fed to bullocks being fattened in the feeding boxes at the farm. In four of the boxes the bullocks were given the same amounts of roots, straw-chaff and litter. No extra feed was given to the animals in two boxes; they produced 'ordinary' manure; in the other two boxes the animals got either cotton cake or maize meal and produced enriched manures.

Sixteen acres of Stackyard were divided into four four-acre blocks (this part of the field is still divided in the same way) so that all four crops of the four-course rotation, roots (mangolds or swedes), barley, clover, wheat, were grown every year. Each block was divided into four one-acre plots so that the plots were sufficiently large for sheep to be penned on them. In each block plot 1 always received the decorticated cotton cake treatment, plot 2 the maize meal, plot 3 fertilisers equivalent to cotton cake, plot 4 fertilisers equivalent to maize meal.

The experiment was started on two blocks in 1877 when clover and roots were grown; the other two blocks started with the same two crops the following year. The root crop was manured with FYM, plots 1 and 2 getting the enriched FYMs, plots 3 and 4 ordinary FYM plus the extra fertilisers. Because it was thought that the fertiliser N to be given to plot 3 was too much for the root crop the dressing was split, two-thirds to the roots, one-third to the following barley. The roots on each plot were weighed before they were eaten by sheep. Barley followed the roots and clover was undersown in the barley. Once established the clover was grazed by sheep given equal weights of decorticated cotton cake and maize meal on plots 1 and 2 respectively; no extra feed was given on plots 3 and 4. Ten sheep were penned on each plot and their live weight increase was measured. The clover was ploughed in early autumn and followed by winter wheat. No fertilisers were given where cake or corn had been fed but on plots 3 and 4 NPKMg equal to that in the cake and meal respectively were applied.

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The results for the first eight years were summarised by Voelcker (1897). He showed that when yields on plots 1 and 2 were compared the expensive cotton cake feeding gave only an extra 6 lb liveweight increase in the sheep, 13 cwt/acre more roots and 26 lb/acre more barley whilst wheat yields were less by about 60 lb/acre. Even the smaller amount of fertilisers plus ordinary FYM (plot 4) gave a larger yield of roots than either of the enriched FYMs. The large amount of fertilisers (plot 3) gave 3 tons/acre more roots than the cotton cake FYM and this treatment also gave most barley, probably because it had one-third of the fertiliser N which should have gone to the root crop. However, barley yielded more after roots given enriched FYMs than after roots given ordinary FYM plus the smaller fertiliser dressing. This first year residual effect was probably due to mineralisation of some extra organic N in the enriched FYMs. No manures or fertilisers were applied for the clover. The sheep which were given additional cake (plot 1) or meal (plot 2) had larger liveweight increases than those on plots 3 and 4 where no extra feed was given. Wheat yields on plot 1 and 3 were almost identical and a little less than on plots 2 and 4.

This demonstration that a 'rich' feedingstuff had so little benefit compared to a poorer one was so unexpected that the experiment was modified on a number of occasions between 1885 and 1937 to try to get the results which had been so confidently expected. All failed. E. J. Russell (1966, p. 172) stated that, 'Scientists and farmers alike knew perfectly well that the result was wrong'. However, this is too sweeping a generalisation. How many farmers had made experiments comparing FYMs made with different feedingstuffs? Probably farmers would not be happy with a result which, if taken to its logical conclusion, would give no more compensation for feeding a 'rich' cake than a 'poor' one. Certainly the result has not been explained. Neither Voelcker nor Lawes, the original sponsors of the experiment, left any record of their views. J. A. Voelcker (1923) considered that Woburn was not atypical of much light land used for sheep feeding in the 1870s and the results would be applicable to many similar soils. He thought that the *preconceived* ideas about the extra value of cake feeding over corn feeding on this soil were exaggerated. He suggested that the extra N from cake feeding had been lost in some way. Much of the extra N was probably in the urine as ammonia or readily mineralised organic N so that N could have been lost by volatilisation or leaching. An experiment testing cake-fed and ordinary FYM and also different forms of N and P fertilisers was started in 1904 by Hall at Rothamsted. There was no feeding on the plots and all the produce was removed. Crowther (1946) showed that between 1907 and 1922 the direct effect of cake-fed FYM at Rothamsted was larger than it had been at Woburn but the result did not support the view that cake-fed FYM was much superior to FYM made by feeding corn.

The Rotation experiment at Woburn continued with various modifications on all four blocks until 1910. In 1911 major changes were made and the experiment was continued on only two blocks, only two crops of the four-course rotation were grown each year. The experiment ended after the wheat crops grown in 1936 (Rotation III) and 1937 (Rotation IV). Details of experiments made on each block (now called Series A, B, C and D) after they ceased to be used for the Rotation experiment were given by Johnston (1975a).

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Experiments on wheat and barley grown continuously

Lawes in particular must have been pleased to have the opportunity to test the continuous growing of wheat and barley on light land and to compare the results with those on Broadbalk and Hoosfield at Rothamsted. After allocating land for the Rotation experiment the remainder of Stackyard which was suitable for experiments was about 5.5 acres (2·2 ha). This was halved; one half was used for the wheat experiment, one for the barley. Originally each experiment had 11 quarter-acre plots, nine tested fertilisers, the other two received single and double dressings of FYM. Two amounts of N were tested and ammonium sulphate and sodium nitrate were compared; PKNaMg were always applied together, only one amount of each nutrient was used. The amounts of NPKNaMg tested were the same as those used for cereals at Rothamsted, the dressings of FYM were smaller.

Lawes (1888) summarised the yields for the first ten years. The responses to N, P and K applied together, and to FYM were much the same as at Rothamsted. At Woburn wheat grown continuously yielded almost as much as barley did. Adequately manured, continuous barley yielded only a little less than barley grown in the Rotation experiment but yields of wheat grown continuously were only about three quarters of those where wheat was grown in rotation. The results showed that wheat and barley could be grown continuously on the light land provided sufficient fertiliser was given but Lawes was careful to point out that much hand labour was required to control weeds.

After about 15 years yields, especially of barley, began to decline where ammonium sulphate was given. This fertiliser had been used for longer at Rothamsted without any deleterious effect but this was on a soil containing as much as 5% calcium carbonate. It was not until the 1940s–50s that yields of cereals at Rothamsted began to decline where ammonium sulphate had been used for 100 years. No evidence now exists to show how the decline in yield was explained in 1890 when the acidifying effect of ammonium sulphate was not known. However in autumn 1897 a number of plots were halved and one half of each plot was dressed with 2 tons/acre of lime (equivalent to 5 t ha^{-1} CaO). There was an immediate improvement in the crop. Between 1898 and 1921 various plots were halved or quartered to test new or additional dressings of lime. The effect of each new dressing was always to increase the yield of both wheat and barley. Recently Johnston and Chater (1975) have determined the pH of most of the soil samples taken from this experiment and discussed the changes in pH with different manurial treatments and liming.

Voelcker (1923) pointed out that this experimental evidence for the beneficial effect of liming was the first to be obtained in this country, although Wheeler at Rhode Island, USA was working on the same problem in the early 1890s. The benefit of liming acid soils is now generally recognised and Voelcker considered that if this had been Woburn's only contribution to British Agriculture then its existence would have been justified. Voelcker and Hall used the results to make their proposals for compensation for the unexhausted value of lime dressings. They used the difference in yield between limed and unlimed plots to assess the period during which lime dressings were effective. Because very small amounts of lime have a beneficial effect at the pH to which these soils had declined the residual effect lasted many years. In 1913 they suggested that compensation should be paid on an eight-year principle,

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i.e. one-eighth is subtracted for each year after application. This was not altered in 1946 when new tables were published (Crowther, 1946).

The Continuous Wheat and Barley experiments well illustrate the dilemma which must often be resolved by those who have responsibility for long-term experiments. Such experiments, especially if they have well chosen and contrasted treatments, are necessary to monitor changes in biological, chemical and physical properties of soils. They provide results which help to explain what happens in soils which have been similarly treated in agricultural practice and if there are problems remedial treatments can be tried on soils with contrasted histories.

The original aim of the Continuous Wheat and Barley experiments was to see which manurial treatments would best maintain yield when these cereals were grown continuously. Increasing soil acidity caused yield to decline and lime was shown to have a beneficial effect. However a comprehensive test of fresh lime and its residual effects could not be included. So neither the original aims, nor the factors which it became necessary to investigate were tested effectively. In the late 1950s it was realised that the liming test should be taken out of the experiments. Ground chalk was used to raise the pH of all soils first to pH 6 and later to pH 7. The history of the experiment, the yields and the effect of treatment on soil pH and soil N, C, P and K have been described recently (Johnston, 1975a; Johnston and Chater, 1975; Mattingly, Chater and Johnston, 1975). A new long-term liming experiment was started on Stackyard (Series C) in 1962 (p. 24).

Experiments on green manuring

The value of green manures has been tested almost continuously since 1892. Green manuring may be described as the practice of growing one crop to prepare the ground for a second and more important one. Hellriegel's discovery that bacteria in root nodules of legumes fixed atmospheric nitrogen to the benefit of the host plant partly explained why wheat yielded well when it followed clover in the traditional four-course rotation. Voelcker decided to test whether other legumes had the same effect, and to compare the effect of legumes and non-leguminous crops used as green manures. In his first experiment on Lansome barley followed tares (vetches), rape and mustard grown for one year with and without PK. Barley was used as test crop again in 1895, but from 1897 winter wheat was grown. Rape rarely grew well on the light soil and was not often tested in later experiments. A much larger experiment was started on Stackyard in 1911 using one of the four-acre blocks previously used for the Rotation experiment. In this second experiment the green crops were fed off by sheep usually given some supplementary feed. In both the Lansome and Stackyard experiments wheat following tares invariably gave the smallest yield. On Stackyard yields were often smaller than those given by NPK fertilisers in the Continuous Wheat experiment and much smaller than those in the Rotation experiment where wheat followed clover. This result, which was consistent throughout 1897–1925, has never been explained. It was observed that wheat following tares always grew more and looked greener in winter and early spring than did wheat following mustard or rape. This led to the suggestion that the larger crop outgrew the amount of water available on this light soil so that at harvest grain yield was less. Pot experiments provided some confirmation for this suggestion. Wheat

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grown in pots of soil taken from the tares and mustard plots yielded equally well when sufficient water was supplied. Irrigation was not available at that time to confirm this result on a field scale. Green crop samples showed that tares provided more organic matter and more N than mustard did and soil samples showed that this extra N increased total soil N. Like the extra N in manure from decorticated cotton cake, the extra N in the tares failed to increase significantly the yields of following arable crops and, even now, this result is not fully explained.

Experiments on grass and fodder crops

These were all short term experiments. One tested seed mixtures suitable for laying down arable fields to pasture. It started on Great Hill Bottom in 1889 at a time of controversy about whether the best pastures in England owed much of their character to the presence of ryegrass. The experiment was sponsored by Mr Carruthers, the RASE's Consulting Botanist, who was opposed to the inclusion of ryegrass in seed mixtures. During the experiment ryegrass became not only an important constituent of the swards where it had been sown but it also spread to most of the other plots. Another experiment tested Elliot's seed mixtures for pasture. These mixtures included deep rooting plants, e.g. chicory, burnet and kidney vetch; the roots were thought to open up hard stony soils, improving both aeration and drainage.

Broad Mead, a field on the heavier soil, was used between 1890 and 1926 for experiments related to the current farming practices of manuring of grassland. Fertilisers and lime were not applied each year and the plots were usually mown for hay and grazed in alternate years. One interesting feature was that nitrogen fertilisers were not tested, probably because little N was then used on permanent pasture. However yields were always largest when FYM was given, presumably because it supplied N, but the herbage was described as 'coarse'. Always mowing for hay was compared with continuous grazing and alternate mowing and grazing. The grazed plots appeared best and liming improved the grazed swards most. The results indicate a shortcoming in the experimental technique used at that time when grazing animals were involved. No attempt was made to assess the amount of herbage available to stock when they were first put on the plots. Cutting and weighing sample areas was introduced much later.

Much work was done on two other forage crops, clover and lucerne. Testing clover varieties suitable for the light soil began in 1883 and work with NPK fertilisers showed beneficial effects of K. However, clover would not grow continuously on the same plots and tended to die off in patches, a phenomenon known as 'clover sickness' (p. 33). In 1885 Miss Ormerod, Consulting Entomologist to the RASE found an eelworm (*Tylenchus devastatrix*) in many of the dying plants. Carruthers, the Botanist to the Society, attributed the dying off to a fungus. Lucerne, however, was a success. It was thought that it would not grow on the lime-deficient soil on Stackyard but some was drilled in 1889. It grew well without being reseeded for eight years and did not completely die off during the next five. NPK fertilisers were tested alone and in combination and at first they had little effect except that yield diminished where N alone was given. As the experiment continued the beneficial effect of K increased.

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Experiments on other crops including maize and potatoes

Maize was first grown at Woburn in 1894 and 1897. Harvested green for fodder it yielded 50 and 30 t ha^{-1} (20 and 17 tons/acre) respectively in the two years. Sugar beet grown in 1910–12 yielded well, 30–40 t ha^{-1} (12–16 tons/acre) of roots, with a sugar content of 14·5–17·5%. Linseed was grown successfully but soya bean in 1912–14 failed because the variety did not mature before it was killed by frost. Another failure was the attempt to grow gorse for stock feed. The plants grew well but it was necessary to buy a 'Gorse Masticator', a machine used to bruise the stems. However, bullocks and sheep would eat only a little even when it was fed with chaffed hay.

Even before 1914 there had been many experiments on potatoes. Some tested various types of FYM, others compared forms of N and K fertilisers. Magnesium was also tested, as it was for wheat and mangolds. Other experiments included a series during 1892–1911 on preventing 'potato disease' (blight). These showed the effectiveness of copper sulphate/lime treatments applied to the foliage and subsequently all potato crops on the farm were treated each year. Many substances claimed to prevent 'finger and toe' in swedes were tested between 1896 and 1904. The only effective materials were those containing lime (no specific fungicides were tested). The fact that the fungus (*Plasmodiophora brassicae*) responsible for the disease only flourished in acid soils was not appreciated and the need to maintain soils at a high pH was not obvious.

Recent work on seed rates and N top dressings for wheat was preceded by similar work at Woburn before the First World War. A test of thick versus thin sowing for wheat showed that the thin sowing was best. Sewage sludge, a treatment in the Market Garden experiment, 1942–67, was first used in 1907–14 in experiments done for the Royal Commission on Sewage Disposal.

Experiments on ensilage

Some of the first experiments done on silage making were at Woburn. Not only were different crops used but a detailed analysis of each silage was made, losses in the ensilage process were calculated and the feeding value of the silage was assessed by feeding trials. The Duke of Bedford gave extra facilities for these experiments, which were started by A. Voelcker about the time he published a paper on the 'Chemistry of Ensilage'. In 1884 four silos capable of holding from 20 to 30 tons of green herbage were constructed in a barn in Woburn Park. One detailed account of the first experiment described the 'opening day' when the Duke of Bedford, Voelcker, Carruthers, Lawes, Gilbert and most of the Chemical Committee gathered to inspect the silages. Apparently the silage in one silo was rotten, the smell was terrible and neither cattle, sheep nor pigs would touch it. However, most of the work was much more successful. It showed that good quality silage could only be made from good crops, that care in packing the silos was essential and that good silage would keep. As techniques improved grass silages were produced which gave live weight increases of bullocks almost equal to those given by feeding roots and hay. Later, oat silage did better than roots fed with chaffed straw and an even later experiment showed that silage and hay gave the same live weight increases. In the last experiment fresh grass from a 5·5 acre meadow was halved, one half was made into hay, the other into silage. The hay and

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silage each provided 84 days feeding for six bullocks and both groups of animals made the same liveweight gains.

Experiments on feeding bullocks and sheep and on calf-rearing

Feeding experiments were made from 1876 to 1901, those with bullocks were done in the feeding boxes, those with sheep were in the open. Different feedingstuffs were compared and the quantities consumed and increases in live weights were measured. The extent to which imported foods could be replaced by home produced ones was determined and also whether less expensive foods could take the place of expensive ones.

The object of the calf rearing experiments, 1912–18, was to see whether whole milk could be replaced by other feeds during the first 10 to 14 weeks of the calf's life. The effects were measured as increases in live weight at the end of this first period. However, any subsequent benefit from each feed was also assessed. After the first period all calves received the same food until they were ready to go to the butcher when their weights were again measured. It was found that the calves which grew fastest in the first period continued to make most growth later.

The results were given in detail in the Society's Journal and summarised by Voelcker (1923). Much of what was found passed into practice and the experiments which provided the information were forgotten.

Experiments on farmyard manure

These experiments, made in 1899–1901, were amongst the first to measure losses of N during the making and storing of FYM. Many analyses were made and the results largely confirmed assumptions made by Lawes and Gilbert about losses of N in FYM which they used in their tables of Manurial Values published in 1897 and 1898. Later work, both in this country and abroad, confirmed the accuracy of these early experiments.

Although there was no doubt about Lawes and Gilbert's estimates of the amounts of N retained in animal carcasses, the amounts of N which reached the field in FYM had not been investigated. By the mid-1880s it was obvious that the 'rich' cake-fed FYM had done little better than the poorer corn-fed FYM in the Rotation experiment on Stackyard.

Bullocks were weighed before and after fattening in the feeding boxes and the N retained in the increased carcass weight was calculated using Lawes and Gilbert's tables. All the food given was weighed and analysed as was the litter. The amount of N excreted by the animals was calculated and added to that in the litter to find how much should have been in the manure. The manure was weighed and sampled for analysis as it was taken from the boxes. It always contained less N than expected. The loss was about 15% even though the manure was made under cover in boxes from which there was no seepage. Later work done elsewhere showed that these were gaseous losses, partly due to direct volatilisation, partly to microbial activity.

The manure from the boxes was made into heaps and covered with earth to prevent leaching. Although no liquid was lost by seepage there was a further considerable loss of N, about 15% during six months storage. So under these almost ideal conditions about 30% of the N in faeces, urine and litter was lost. Under more average farming conditions the usual estimate of 50% loss of N is not excessive.

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Experiments in the glasshouse

Mr Hills bequest (p. 7) was for experiments to be made on the 'rarer forms of ash' in which he included 'fluorine, manganese, iodine, bromine, titanium and lithia'; at that time little was known about trace elements. The experiments were made on plants grown in pots and much had to be learnt about the techniques for doing this. Large zinc pots, 25 cm (10 in) diameter by 25 cm depth, or glazed earthenware pots, 28 cm (11 in) diameter by 28 cm depth, were used. Soil to fill the pots was taken from the field, about 15 kg (34 lb), dry soil was needed for each pot. Wheat was usually used as the test crop, although various root and legume crops were also tried.

The materials tested in the first year were: calcium fluoride, calcium oxide, manganese oxide, sodium iodide, sodium bromide, sodium chloride, titanium oxide, ferric oxide, lithium chloride and calcium chloride. All were tested at a rate equivalent to a dressing of 630 kg ha^{-1} (5 cwt/acre). In many pots seeds failed to germinate and those that did grew poorly. Very few plants grew well and subsequently much time and effort was spent finding the amounts of these and other elements which could be applied without inhibiting growth. The other elements tested included caesium, cerium, zinc, lead, copper, strontium, boron, barium, iron, arsenic, tin and chromium.

The tragedy of the work done under the Hills Bequest was that, as early as 1899, experiments were made which gave leads for further work but these leads were not effectively followed. Plants grown from seeds soaked for 10 minutes in very dilute solutions of a number of salts were better than untreated controls. The inference that only a minute amount of the element was required was missed. Also in 1899 nutrient culture experiments were tried using tall glass jars. The technique allowed both root and shoot growth to be observed as well as control of nutrients available to the plant. It was not until much later, and then not at Woburn, that nutrient culture techniques were improved and used to investigate the role of trace elements in plant nutrition.

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Recent Experiments

At present four farms are controlled by the Lawes Agricultural Trust. Besides Rothamsted and Woburn there are Broom's Barn, 80 ha (198 acres), principally concerned with growing sugar beet and Saxmundham, which is small, 3 ha (7 acres), where the emphasis is mainly on plant nutrition on Chalky Boulder Clay soil. Rothamsted is divided into Departments based on scientific disciplines rather than into groups working on single crops. Individuals or groups from a Department often make field experiments but more frequently now experiments are sponsored by groups of individuals each from a different discipline. However, it is easier in this account to describe the work done by Departments which are listed alphabetically. Some Departments have been more heavily committed than others because of the problems encountered at Woburn. Before describing the work of each Department two comments should be made; one about the early history of Stackyard, one about current farm practice.

The early history of Stackyard Field

In the 1880s Lawes attempted to discover something of the early history of Stackyard Field to try to explain why crops had not responded to cake-fed FYM in the Rotation experiment (p. 12). It was thought that the varieties grown were yielding their maximum with all treatments because the soils were very fertile. Mann pursued these enquiries further with the Duke of Bedford's Agent in the 1930s. In a recent search of old records a map of the district dated 1822 was found on which Stackyard was named as Stackyard Meadow. This suggests that the field was a pasture at that time. Lawes's enquiries elicited the fact that the earliest record of arable cropping was in 1866 and for the next ten years the field was cropped on a four-course rotation. He also found that the field was probably in grass in the 1830s–40s but it could well have been ploughed about that time when there was a great expansion in arable farming in England. During the period of arable cropping the roots were usually manured with farmyard manure (FYM) and those not required for cattle were fed off, as was the aftermath of the clover crop, by sheep given supplementary feed during the winter. The probability that the field had been in grass for a long period followed by arable crops generously manured with FYM, may explain why the soil contained so much more organic matter in 1876 than it does today. Changes in soil organic matter are discussed later (p. 22).

It is probable that in the 1930s–40s declining organic matter in the soil had little effect on yield. Mann (1959) could find no evidence for deterioration in yields in the Six-Course Rotation experiment between 1930 and 1955. The amounts of fertiliser used and the yield potential of the varieties grown were probably more important limiting factors. Recently as a result of controlling pests and diseases, using more fertiliser and growing better varieties yields

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have increased and there is some indication that the increase may be larger on soils with more organic matter (p. 23).

Current farm practice

Many experiments at Woburn occupy the same site each year because the work involves monitoring changes in pests, diseases or soil nutrients due to cropping, manuring and other treatments. Proportionally there are many fewer annual experiments at Woburn than at Rothamsted. To provide sites of known history for annual experiments those parts of the experimental fields not used for long-term experiments follow a six-course rotation: beans, wheat, barley, two-year break, wheat. The two-year break can be a one or two year fallow, especially if rhizomatous grass weeds are to be controlled, a one- or two-year ley or two non-cereal crops, potatoes are usually taken in the second year. Nematode-resistant potatoes are occasionally grown in place of beans.

To prevent serious acidity developing most fields in the six-course rotation are now limed with dolomitic limestone, 7·5 t ha^{-1} (3 tons/acre), once in the rotation, usually to the wheat stubble before beans. This magnesian limestone maintains soil magnesium. In some years during the 1950s crops showed visual symptoms of Mg deficiency. In experiments where ground chalk is still used to maintain soil pH yields are often increased by giving Mg. In many experiments more than one amount of N is tested. Basal dressings of P and K fertilisers are applied each year, the amounts vary according to the crop.

Botany Department

Until 1955 the Department's main interest at Woburn was the weeds characteristic of light or acid soils. These included long-headed poppy (*Papaver dubium*), corn spurrey (*Spergula arrensis*), annual nettle (*Urtica urens*), wild chamomile (*Matricaria recucita*) and common bent grass (*Agrostis gigantea*). The last named is now abundant in several places at Rothamsted; it is thought to have been brought from Woburn. In 1927–29 Brenchley and Warington (1930, 1933) studied the buried weed seed populations in soil from the Continuous Wheat and Barley experiments and compared the results with those from Broadbalk at Rothamsted. Recently possible methods of chemical control of *Equisetum* were tested in Lansome where this weed occurs in a small area.

In 1955 the effects of irrigation on the growth of sugar beet were studied. The experiment showed that after a drought a small amount of rain, much less than that needed to eliminate the water deficit, increased both growth rate and leaf efficiency above that on the fully irrigated crop (Owen and Watson, 1956). This could be important in relation to the efficient use of irrigation water and forms the basis of work on the application of minimal amounts of irrigation water since carried out by Broom's Barn and the University of Reading.

The growth and development of arable crops has been studied in some detail. At Rothamsted the contribution of above-ground parts, and leaves in particular, to final yield, has been measured. At Woburn factors affecting root development have been studied on the light, relatively stone-free soil

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which offers no serious impedance to root growth to a great depth. Both root length and total dry weight have been determined in soil cores usually taken to 1 m. The 7 cm diameter cores are taken with a coring tube hammered mechanically into the soil and withdrawn with a hand hoist. The cores are divided into layers varying from 10 to 30 cm to investigate root distribution at different depths.

Experiments were made on barley, oats and semi-dwarf and taller varieties of wheat. The effect of NPK fertilisers, light intensity, plant population and irrigation have been studied. There were most roots at, or soon after, anthesis and as many as 60–70% of these were in the top 15 cm of soil. Usually N depressed root growth initially and extra P and K frequently had little effect on roots in the soils used for these experiments. Shading during the period of most active vegetative growth also decreased root production.

Winter and spring wheat, barley and oats were all grown in one experiment. Winter wheat roots had already reached 30 cm when the spring cereals were sown. At the end of June oats and winter wheat had the largest weight of roots but barley had the greatest length. In other experiments winter wheat roots had extended to 60 or 70 cm by early spring which suggests that winter wheat could recover fertiliser N leached to that depth by rain.

Collaborative work on winter wheat with the Plant Breeding Institute and the ARC Letcombe Laboratory included studies on the uptake of radioactive P from different depths in soil and the estimation of root distribution using radioactive rubidium injected into plants via the shoot bases. Varieties as different in shoot habit as Cappelle-Desprez, Maris Ranger, Maris Fundin and Hobbit were found to have very similar amounts of roots and root distribution within the soil (Welbank *et al.*, 1974).

Chemistry Department

Changes in soil organic matter and plant nutrients due to cropping and manuring have been determined during many years. Lawes took soil samples from Stackyard in 1876 before the experiments started, sampling the profile by 23 cm (9 in) depths to 138 cm (54 in). The 0–23 and 23–46 cm depths on various plots were sampled again in 1888, 1898, 1927 and 1932. Many analyses were done on these soils at Rothamsted (Crowther, 1936). The samples still exist and many have been reanalysed recently. The soils were sampled again in the 1950s and 1960s.

The effect of treatment on soil N and C under continuous cereals and a rotation of crops has been measured. In 1876 the soil contained 0·156% N, much more than it does today. This may be explained by the previous history of the field (p. 20). When cereals were grown continuously soil N had decreased from 0·156% N to 0·094% N under wheat and 0·084% N under barley in 1959 on soils which were unmanured or given inorganic fertilisers. FYM applied at about 20 t ha^{-1} (8 tons/acre) during 1877–1906 increased soil N a little by 1888 but in 1907 the FYM dressing was decreased to 15 t ha^{-1} and by 1927 soil N had declined to 0·148% N, a little less than at the start of the experiment. No FYM was given after 1926 and soil N diminished rapidly. In 1959 the extra N in the soil was only 0·013% N, about 8% of the total N applied in the manure between 1876 and 1926. Rotational cropping between 1876 and 1937 did little to prevent a similar decline in soil organic matter on the remainder of Stackyard. During this period crop yields and therefore the

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The farm house about 1890

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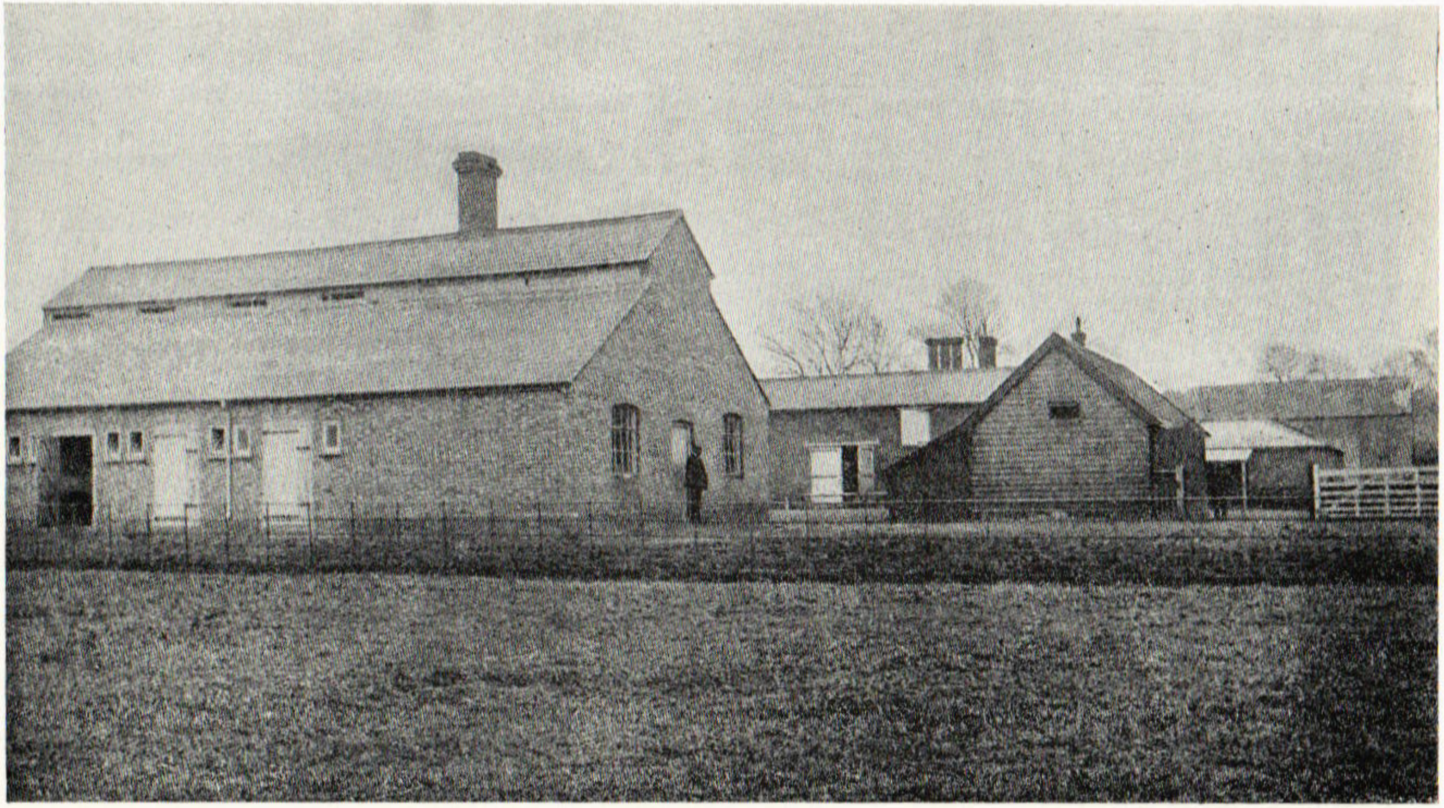

Building containing the feeding boxes erected 1876

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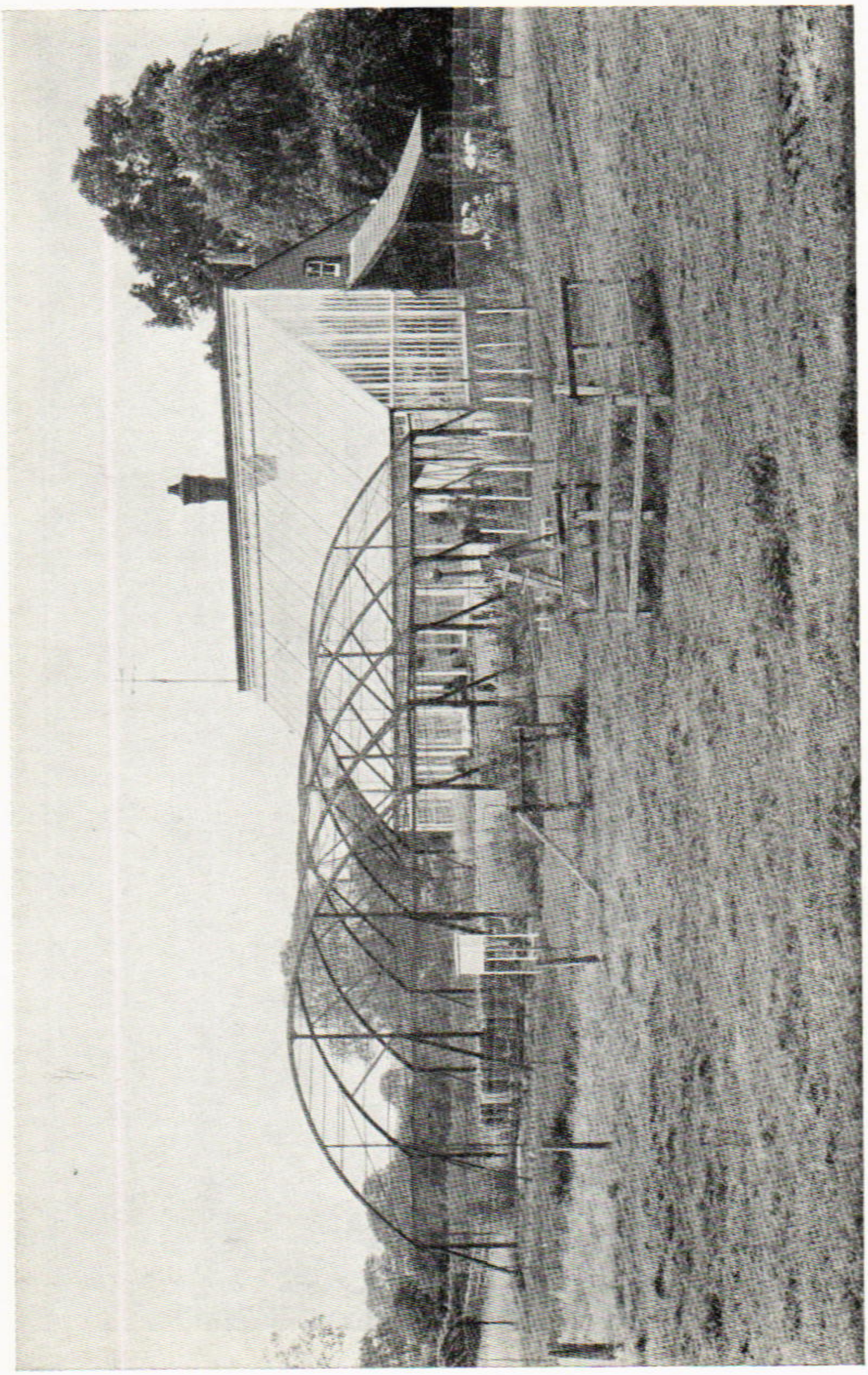

'The Cage', glasshouse and laboratory, about 1900

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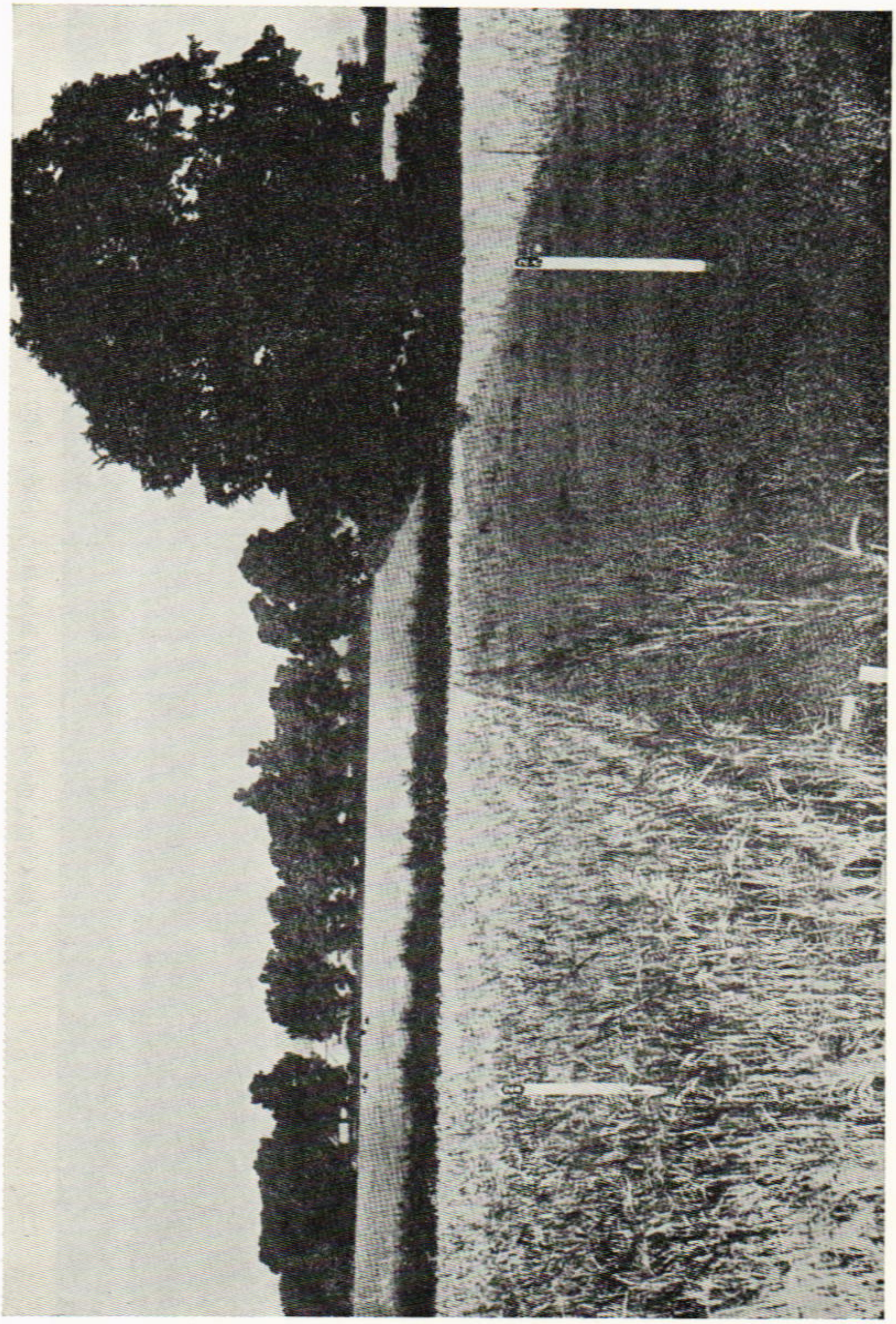

Effect of soil acidity on the growth of barley: the Continuous Barley Experiment, Stackyard Field, about 1900

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return of organic residues as roots and stubble were small (Mattingly, Chater and Johnston, 1975). Recently, where much larger arable crops have been grown, the decline in soil organic matter appears to have been halted.

In a five-course rotation experiment where three-year leys were followed by two arable crops, one of which received FYM, soil organic carbon increased during 33 years but only from 1·02 to 1·44% C (Johnston, 1973). To achieve large increases in soil organic matter it would appear that the land must be in grass for many years.

The Agricultural Advisory Council's 1970 Report, *Modern Farming and the Soil*, commented on the importance of soil organic matter and gave prominence to critical values for the amounts needed in certain soils. However this problem is difficult to experiment on because it is not easy to get soils with different amounts of organic matter but the same amount of plant nutrients.

Early results from the Ley Arable and Market Garden experiments cannot be used to estimate the effects of extra soil organic matter because soils with most organic matter also had most P and K. In the Ley Arable experiment P and K were both increased during the 1960s to amounts which were thought unlikely to limit crop growth and the opportunity was then taken to determine the effects of nematodes and fungal diseases especially on potatoes (p. 28). These tests only recently ended and from 1977 all soils will be treated with aldicarb as they come into test crops and any effects of organic matter will now be measured. In the Market Garden experiment very large dressings of bulky organic manures were applied during 1942–67; e.g. 1800 t FYM ha^{-1} (720 tons/acre) and 1400 t sewage sludge ha^{-1} (570 tons/acre). These dressings supplied much P or K or both and it was almost impossible to get the same amounts of soluble P and K in soils with and without organic manures. However amounts of P and K were thought to be non-limiting in any soil in 1966 when red beet were grown with four amounts of N. Maximum yields were about 35 t marketable roots ha^{-1} (14 tons/acre) and with each amount of N tested soils with most organic matter yielded more than soils with least (Johnston and Wedderburn, 1975).

A new experiment to determine the effects of organic matter was started in 1965 and during the first six years, whilst different amounts of organic matter were being added to the soil, the PKMg additions were carefully balanced (Mattingly, 1974; Mattingly, Chater and Poulton, 1974). Since 1972 wheat, barley, potatoes and sugar beet have been grown; eight amounts of N were tested on each crop. Yields of all four crops, especially the potatoes and sugar beet, have benefited from the extra organic matter at all levels of N.

The light soil at Woburn does not hold as much exchangeable K as the heavier soil at Rothamsted and one problem with nutrient balancing has been to maintain exchangeable soil K. Only a little of the K added to the slightly acid Woburn soil becomes non-exchangeable and it is possible to balance exchangeable K in differently treated soils quickly. This has been done in the Ley Arable experiment. However K is relatively easily leached from the surface soil. Where much K has been applied in the Market Garden experiment there is the same amount of exchangeable K to a depth of 70 cm (27 in) (Johnston, 1975b). A pot experiment in the glasshouse at Rothamsted has shown that much exchangeable K lower down the profile is available to plants provided their roots can reach it.

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Another problem on these poorly buffered, slightly acid soils, which are also low in organic matter, is the movement of biologically active compounds. Simazine applied to control weeds in beans has been leached down by heavy rain sufficiently quickly to damage the beans. Surface applied 2,4-D and metobromuron were leached down to 125 and 75 mm respectively (5 and 3 in) by 22 mm of rain in a soil with only 0·7% organic carbon, almost three times as far as in a soil with 3·5% C. Benomyl and carbendazim are adsorbed by the mineral fraction in these soils and were not leached below 25 mm by more than 500 mm of rain (Austin and Briggs, 1976).

Soils from the continuous cereals experiments had pHs more acid than those of many Rothamsted soils in the 1920s, so they were used in studies on methods of determining pH. The work was extended to the determination of exchangeable bases and the effects of manures and liming on both exchangeable cations and pH (Crowther, 1936). The effects of recent liming has been mentioned (p. 15). Regular liming, as now practised at Woburn (p. 21), is essential to prevent soil acidity adversely affecting yield.

An experiment specifically designed to study effects of liming was started in 1962. Limestone at 0, 5, 12 and 19 t $CaCO_3$ ha^{-1} (0, 2, 4·8, 7·5 tons/acre) applied in 1962 is tested factorally with P and K applied each year. By 1967 the soils had pHs of 5·0, 6·2, 7·0 and 7·4. Largest yields of beans and barley were on soils above pH 6·5 and when P and K were both given. Responses to P were larger at low than at high pH. Yields of potatoes and oats were unaffected by soil pH over the range tested when adequate NPKMg were given. Responses to P and Mg were large especially at low pH and response to K was similar over the whole range of pH or was larger at high pH. Soil analysis showed that the annual loss of Ca was equivalent to 307 kg $CaCO_3$ ha^{-1} year^{-1} at pH 5·4 and 752 kg $CaCO_3$ ha^{-1} year^{-1} at pH 7·4 equivalent to 2·45 and 6 cwt $CaCO_3$/acre/year (Bolton, 1977a and b).

An experiment begun in 1960 measures the effects of FYM and NPK fertilisers on a five-course rotation of barley, grass-clover ley, potatoes, oats and sugar beet and on a permanent ley. Mg was tested from 1966 on sugar beet and from 1968 on potatoes. N greatly increased the yield of all crops other than the clover-rich rotational ley and K greatly increased the yields of all except oats. Barley and oats were the most responsive to N and potatoes, sugar beet and the long ley were most responsive to K. P increased yields little on the soil used for this experiment. Responses to both N and K, measured as yield with N or K *minus* yield without N or K, were larger during 1965–69 than in 1960–64. The response to K probably increased because part of the soil K reserves were depleted during the first period and yields without K were proportionally less in the second period. FYM given to potatoes and sugar beet increased yields and barley and oats benefited from the residues. Fertilisers plus FYM gave by far the largest yields of potatoes and sugar beet and FYM residues plus fertilisers gave larger yields of the other crops except oats. On fertiliser-treated soil Mg increased the yields of potatoes and sugar beet most when K was also given, but fertiliser Mg had no effect when applied with FYM. During 1965–69 best yields were: potato tubers, 55 t ha^{-1}, sugar beet roots, 49 t ha^{-1}, barley, 4·66 t ha^{-1}, oats, 5·47 t ha^{-1} (Widdowson and Penny, 1972). Nutrient uptakes were measured to calculate the nutrient balance, additions *minus* removals. For P and K the balance was related to changes in readily soluble P and K in the soil (Williams, 1973).

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Other experiments showed that the large potato yields given by FYM plus fertilisers mentioned above could be explained by the fact that too little fertiliser was given for maximum yield. When larger amounts of fertiliser were tested yield increased but the large fertiliser dressings had to be deeply incorporated with the soil to be safe and fully effective (Widdowson, Penny and Flint, 1974).

The light soil at Woburn does not require under drainage but six land drains have been put in at various times. The drainage from each is sampled and analysed for the plant nutrients it contains. Drainage flow rates can be estimated but nutrient losses per hectare cannot be calculated because the area from which the drainage is collected is not known. One very shallow drain carries much more nutrients than the other five. If this drain is omitted the average annual loss from each of the five drains amounts to 40 kg NO_3-N, 7 kg K and 0·2 kg P. Local mainswater pumped from the aquifer in the Greensand below the district contains, on average, 4 mg litre^{-1} NO_3-N (range 0·01 to 8.5 mg litre^{-1}) well below the upper limit (11·3 mg litre^{-1}) recommended by the World Health Organisation for potable waters (Williams, 1976).

Field Experiments Section and Farm

In the Green Manuring experiments started by Voelcker (p. 15) green manures occupied the land for one growing season. Today it is unlikely that green manures would be used in this way in established farming systems, as opposed to land reclamation, unless they could be used profitably, perhaps as feed for stock. So the effects of trefoil and ryegrass grown as catch crops have been tested recently in farming systems in which one cash crop was grown each year. The green crops usually occupied the land during autumn and winter and were ploughed in for a spring sown crop. The ryegrass could have taken up any residual N in the soil from previous manuring, trefoil could have fixed atmospheric N. Four amounts of fertiliser N were usually tested on the potatoes, sugar beet or barley grown as test crops. In some circumstances green manures gave extra yield at all amounts of fertiliser N tested. When yields with and without green manures were the same less fertiliser N was needed where green manures had been ploughed in. However at present prices the use of green manures is unlikely to be immediately profitable to many farmers. Green manures taken as catch crops each year maintained or slightly increased soil organic matter on this light soil (Dyke, Patterson and Barnes, 1977).

The effects of migratory nematodes and fertiliser N on yields of spring beans were tested during 1969–71. The soil had not grown beans for at least 25 years but it was known to be infested with migratory nematodes. When these were controlled with dazomet yield increased by about 20%. Fertiliser N in amounts up to 250 kg N ha^{-1} decreased yield on untreated soil but gave a larger yield than dazomet alone on treated soil. Fertiliser N did not affect nematode numbers or root blackening. Dazomet greatly decreased migratory nematodes but did not affect root blackening. Dazomet almost eliminated mycorrhizal infection by *Endogone* spp.; in untreated soil infection was increased by fertiliser N (McEwen, Salt and Hornby, 1973).

Average annual rainfall is about 620 mm at Woburn and lack of summer rain is thought to limit yield. On many fields a layer of denser soil can be

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detected about plough depth if sampling is done at the right moisture content but roots will grow through this layer if it remains wet. Below the layer the soil is readily penetrated by roots. In 1974 an experiment was started to determine the effects of subsoiling and enriching the subsoil with P and K on the yields of a rotation of crops: wheat, sugar beet, barley and potatoes. The experiment is a small one, the subsoiling was done by hand forking after the topsoil had been removed; as the subsoiling was finished the topsoil was replaced. So far subsoiling has benefited all crops except potatoes. Enriching the subsoil increased yields, in addition to the effect of subsoiling, of sugar beet, barley and potatoes but not wheat.

In anticipation of an increasing acreage of maize and because little was known about pests and diseases of maize likely to be important in this country, an experiment was started in 1971 in which maize is grown continuously. Nitrogen is tested at 50, 100, 150 kg N ha^{-1} to the seedbed and 100 kg to the seedbed plus 50 kg topdressed later. Half the soils are treated with dazomet. During 1971–74 grain varieties were grown, in 1975–76 forage maize was planted. Yields have been maintained so far. There has been a slight but not significant increase in some diseases and frit fly (*Oscinella frit*) causes some damage in most years. Dazomet has lessened the number of free-living nematodes (*Pratylencus* spp.) and yields are about 1 t dry matter ha^{-1} more on dazomet-treated soil. Yields are least on untreated soil given the smallest amount of N; the response to N is larger on untreated soil than where dazomet is applied.

Three primary cultivation techniques, mouldboard ploughing, rotary cultivating and working the land with a deep-tined cultivator, were compared during 1961–67. All primary cultivations were followed by appropriate seedbed-producing operations. Mechanical cultivations and herbicides were compared for post-planting weed control. The three prime cultivations gave similar yields of all crops tested, potatoes, beans and barley, but weeds were fewer where a mouldboard plough was used. Herbicides applied to beans and potatoes controlled most weeds (other than graminaceous ones) without decreasing yield appreciably nor did the herbicide residues affect the yield of the following crop (Moffatt, 1966).

Direct drilling of winter wheat into land sprayed with weed killer (paraquat) was compared with drilling into seedbeds produced after mouldboard ploughing during 1966–71. Before this experiment the site was permanent pasture, wheat was then grown continuously; plots were always ploughed or direct drilled. Average yields were not large, 3·55 t ha^{-1} (28·3 cwt/acre) and 3·59 t ha^{-1} (28·6 cwt/acre) after direct drilling and ploughing respectively. In the second year direct drilled wheat was severely attacked by slugs but there was no obvious damage on ploughed plots; yields for this year are omitted from the averages given above. The effects of the treatments on earthworm populations were estimated. There are usually more earthworms in grassland than in arable soils and the gradual decline in *Lumbricus terrestris* in all soils was not unexpected, but unploughed soils always had most. The populations of other species were about equal in 1967 under ploughing and direct drilling but they subsequently decreased more on unploughed soils. This difference probably occurred because direct drilling failed to incorporate fresh organic matter in the surface layers of soil where species other than *L. terrestris* live. By contrast *L. terrestris* pulls litter deep down and so would probably suffer less from lack of incorporated organic matter than other species would (Edwards,

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Lofty and Whiting, 1972). In general there were more migratory plant parasitic nematodes in soil which was ploughed but some non-parasitic nematodes were more numerous in unploughed soil (Corbett and Webb, 1970).

Insecticides and Fungicides Department

As part of its comprehensive programme aimed at making crop protection safer and more efficient, the department has for many years studied the naturally-occurring pyrethrins in *Chrysanthemum cinerariaefolium* and their synthetic analogues which are highly toxic to insects but outstandingly safe to mammals. This work included field experiments at Woburn which showed that the fertiliser requirements of *C. cinerariaefolium* were small (Tattersfield, 1937).

During and after the Second World War, the Department was associated with the introduction of DDT and some of the first samples available in this country came to Rothamsted. In 1943–44 the effectiveness of DDT against pests of carrots, cabbage and beans was assessed at Woburn in what were among the first field trials of DDT in this country (*Rothamsted Report for 1939–45*).

Other studies on insect control have included work on aphids. The abundance of *Aphis fabae* and the incidence of pea leaf-roll virus on field beans (*Vicia fabae*) were shown to be inversely related to planting density (Way and Heathcote, 1966).

The light soil at Woburn favours the soil-borne fungus, *Streptomyces scabies*, the cause of potato common scab, but soil fungicides are not very efficient at controlling the incidence of the disease. Recently however, scab has been decreased by certain chemicals applied to the foliage. These chemicals appear to offer the prospect of a new method of controlling not only scab but other soil-borne diseases (McIntosh, 1975).

Woburn soil has also been used for physico-chemical studies on the behaviour of systemic pesticides in soil and their availability for uptake by plant roots (Graham-Bryce, 1968). Related field and pot experiments with potatoes and beans have identified factors governing the performance of granular formulations of insecticides. Rainfall in particular has a marked influence on the performance of both foliar and soil treatments (Etheridge and Graham-Bryce, 1970; Graham-Bryce, Stevenson and Etheridge, 1972).

Nematology Department

Observations at the four farms controlled by the Lawes Trust suggest that only at Woburn do many crops suffer appreciably from attacks by nematodes, except at Rothamsted where stem nematodes can cause much damage. It is probable that the particle size distribution of the soil and the large amount of coarse sand combine to give a range of pore sizes especially favourable to the movement of nematodes. Cereal and potato cyst-nematodes occur in most fields. Lucerne in the Ley Arable experiment was so severely attacked by stem nematodes that it could no longer be grown and field beans are often attacked by stem nematodes spread around Rothamsted and Woburn Farms in infested seed. Most crops at Woburn are attacked to some extent by root ectoparasitic nematodes which usually cause most damage when a dry spell of weather in June and July follows a wet May.

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Much work has developed from studies made on the Ley Arable experiment in the early 1950s and this is a good illustration of how a long-term experiment can continue to provide useful information. During 1938–55 potatoes were grown eight times on soils in the continuous arable sequences but only three times in the ley sequences. In 1955 yields were larger after leys than after continuous arable because the latter soils had become heavily infested with potato cyst-nematode (*Globodera rostochiensis* Ro 1). At that time the only effective control was to stop growing potatoes frequently and sugar beet replaced potatoes as first test crop. Potatoes continued to be grown as a treatment crop, once in five years in the continuous arable but only once in 10 years in the alternating ley and arable sequences. Subsequently Maris Piper, a potato variety resistant to *G. rostochiensis* Ro 1, was grown as the treatment crop and numbers of *G. rostochiensis* declined to a population thought unlikely to affect yields seriously. However, potatoes still yielded less in the continuous arable sequences, in some years by as much as 29 t ha^{-1} (12 tons/acre). A joint investigation with the Plant Pathology Department showed that the fungus *Verticillium dahliae* was not the cause and suggested that one or more species of root ectoparasitic nematode was responsible. An injurious species of needle nematode, *Longidorus leptocephalus*, was found in large numbers below plough depth. Feeding on the deeper roots it seemed to check growth and yellowing occurred in July when water stress developed (Evans and Pandé, 1972).

Early work on the Ley Arable experiment showed that both for research and advisory work it was necessary to measure nematode distribution and population changes within fields. This work was pioneered at Woburn in the 1950s (Fenwick, 1961). This and other investigations subsequently led to much work on population dynamics and population control (Jones, Parrott and Ross, 1967; Jones and Kempton, 1977).

Once populations could be estimated it was possible to measure the effects of treatments designed to control nematodes. Initially efforts were concentrated on the control of potato cyst-nematodes and it was shown that this could be achieved by nematicides (Whitehead, 1975). The experiments demonstrated the importance of different methods of distribution and incorporation of granular nematicides and emphasised the need to control nematodes below plough depth. The extent to which control could be achieved by growing resistant varieties of potatoes or by changes in cropping or by fallowing were determined. The object of all these experiments has been not only to increase yields but to improve 'kills' so that survivors were unable to multiply fast enough to regain, or surpass, the numbers present at planting. Recent improvements in farm practice are aimed at producing potato crops in excess of 30 tons/acre. This may have a considerable effect on the numbers of nematodes and this is being studied.

Work in the laboratory has shown that the dominant potato cyst-nematode at Woburn is *Globodera rostochiensis* Ro 1 (formerly pathotype A) but *G. pallida* Pa 3 (formerly pathotype E) is present, notably in Butt Close. Its presence became apparent after several crops of the potato variety Maris Piper resistant to *G. rostochiensis* Ro 1 but susceptible to *G. pallida* Pa 3 had been grown (Parrott, Berry and Matthews, 1973).

The beneficial effect of additional N fertiliser, but not P or K, for potatoes grown on soil infested with cyst-nematode was demonstrated in 1956 (Jones, 1977). Later, joint work with Chemistry and Physics Departments led to the

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following summary: *G. rostochiensis* and *G. pallida* cause potato roots to be smaller and more branched. The roots explore a smaller soil volume and take up water and nutrients less efficiently. Both water and nutrients are shunted to the exterior through the bodies of established female nematodes. The number of leaves per stem is not affected but the leaves are smaller and the stems are fewer and shorter. Infected plants have a larger % dry matter and in the dry matter concentrations of Ca and Na are increased, N is unchanged and P, Mg and especially K, are all decreased. Because yields are diminished appreciably the uptake per hectare of all nutrients is smaller than in healthy plants (Evans, 1975).

Not only are there two species of potato cyst-nematode at Woburn but there are two sub-species of *Heterodera avenae*, the cereal cyst-nematode. Population changes have been monitored when resistant and susceptible cereal varieties were grown and it was shown that *H. avenae* usually failed to increase when susceptible cereal hosts were grown continuously (Williams, 1969). An explanation was sought and the first clue came from an experiment in which a formalin drench was used as a soil treatment, nematode numbers increased more in formalin treated soil than in untreated soil. There are two possible explanations, firstly formalin is a poor nematicide and it may have killed sufficient nematodes in the year of application for the crop to benefit but subsequently the population may have increased rapidly. Secondly, the formalin might have killed many enemies of the nematodes. One such enemy is now known to be an Entomophthora-like fungus which attacks young females in May–June (Kerry, 1976).

Recent work has been extended to the dynamics and control of stem nematodes, particularly the two races that attack beans. The speed with which this pest has increased as a result of drilling infested seed has been alarming and clearly indicates the need to examine all seed particularly that to be used on soils so far free of the nematode. A method of disinfecting seed is being sought and many collections of beans have been screened for resistance, so far without success (Hooper, 1971, 1976).

Physics Department

For almost 20 years the Physics Department's work at Woburn centred on an irrigation experiment started in 1951. The clay content of the Woburn soil restricts infiltration capacity and as level a site as possible was needed to avoid run-off when row crops were irrigated. The only available site was sheltered on the south side and estimates of water need were probably a little smaller than they would have been on a more exposed site in the Woburn area. Irrigation was tested on whole plots which, because of their small size, could only be halved to test one other factor. This was usually extra N. There were four irrigation treatments, unwatered, fully irrigated, fully irrigated early then unwatered, unwatered early then fully irrigated. The division between 'early' and 'late' was usually based on crop development, e.g. ear emergence in cereals, flowering in beans and potatoes. Full irrigation was intended to keep the estimated soil water deficit less than 2·5 cm. Occasionally the deficit increased beyond this and sometimes so much rain fell after irrigation that the deficit was quickly decreased to zero and any surplus rain could then have caused drainage. The crops grown included grass-clover, grass, lucerne and clover leys; early and maincrop potatoes and sugar beet; barley, spring wheat and beans.

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Between 1951 and 1969 there were very wet summers in 1954, 1958 and 1963 with no need for irrigation; the summers of 1955 (after June), 1959 and 1964 were very dry and supplementary watering was obviously beneficial. The experiment sought to find how often irrigation is needed between these extremes. *MAFF Technical Bulletin* No. 4 defines a year of irrigation need as one in which the excess of potential evaporation over rainfall is more than 7·5 cm (3 in) for the period 1 April to 30 September. When the experiment started this was expected to be seven years in ten at Woburn, in the event it happened only ten years in 19. Thus there were not as many years in which to show the benefit of irrigation as had been expected. However in 13 years at least one crop (of the four grown each year) gave more than 20% increase in yield, in ten years at least one crop gave more than 50% increase and in five years at least one crop yield was doubled.

The results were used in helping to compile *MAFF Bulletins* Nos 138 and 202 and *Technical Bulletins* 4 and 16. The Central Advisory Water Committee's Report, *Irrigation in Great Britain*, HMSO, 1962 also made much use of the data. This report suggested that irrigation could be used to increase yield on perhaps 0·6 million ha (1 500 000 acres); however, increased profit might only be possible on a much smaller area (Penman, 1971).

Plant Pathology Department

Disease surveys on Woburn and Rothamsted Farms began in 1930 when it seemed that regular inspection of experimental crops, especially those in classical and long-term experiments, would give information on the effects of manurial and other treatments on crop pests and diseases. The results of the first surveys were published by Mary D. Glynne in the *Rothamsted Reports* from 1930 to 1938. Her surveys initiated detailed work on some diseases and she was the first to recognise the phenomenon now called take-all decline. This was on the Continuous Cereals experiments on Stackyard in 1931–33.

Soil-borne diseases, particularly of cereals and potatoes, have been most studied in recent years with similar experiments being done at Woburn and Rothamsted. The results have not always been the same because at Woburn fungal pathogens often interact with other factors such as soil structure, water holding capacity, loss of nutrients by leaching and the abundance of free-living and endoparasitic nematodes, factors which are not in themselves serious problems at Rothamsted.

Take-all, caused by the fungus *Gaeumannomyces graminis*, is the disease that usually causes most loss of wheat and barley when both are grown frequently at Woburn. The first disease survey on the Continuous Wheat and Barley experiments in 1930 showed that take-all attacked winter sown wheat more severely than spring sown barley. Variations in soil pH, as a result of earlier fertiliser treatment (p. 14) caused differences in the amounts of take-all. There was little or none in both wheat and barley on soils at pH 5 or less but considerably more at higher pH. When the surveys were continued over a number of years it was observed that the amounts of take-all increased to a peak and then decreased in both crops (Glynne, 1935). These observations have been verified on many occasions subsequently. Although take-all decline has important practical implications there is as yet no simple explanation and possible causes are being studied.

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Many experiments have investigated the effects of take-all. Work done jointly with Soil Microbiology Department in the 1940s showed first how to grow good crops of English trefoil (*Medicago lupulina*) by inoculating with the appropriate nodule bacteria. Undersown trefoil was then tested as a catch crop in barley grown continuously. Barley had least take-all and yielded most when grown following barley undersown with trefoil (Garrett and Mann, 1948).

In 1954 a then record yield of winter wheat, 6·28 t ha^{-1} (50 cwt/acre), was grown when wheat followed potatoes and more N than usual was given. In that year yields were much the same in a similar experiment at Rothamsted but in subsequent years yields declined more at Woburn because there was more take-all and weeds, especially *Agrostis gigantea*. These experiments demonstrated that the time of applying N for wheat was much more important at Woburn than at Rothamsted. Wheat given N in April had less take-all and yielded more grain than wheat given N in March or May (Salt, 1959).

To determine the effects of break crops the yields of first, second and third wheat after a two-year break (ley and potatoes) have been compared with yields of wheat grown continuously in the Intensive Cereals experiment. Disease assessments showed that there was most take-all in the third wheat, less in wheat grown continuously and least when wheat follows a break. However it is difficult to relate yield directly to the incidence of disease for yields can vary greatly between years because of factors other than disease. In this experiment crops little affected by take-all yielded 4·14 and 5·02 t ha^{-1} in 1968 and 1969 (33 and 40 cwt/acre) but only 3·26 t ha^{-1} in 1970 (26 cwt/acre) (Slope, 1971).

Recently new techniques have been developed to help study the distribution and persistence of inoculum of *G. graminis*. These include new sampling tools, a wet sieving method for extracting different sized fractions of crop debris from soil and a method of estimating the number of infectious fragments. Information can now be obtained on the behaviour of soil-borne inoculum to help identify times when the fungus may be most vulnerable to control measures (Hornby, 1975).

Using a neutron probe to measure weekly changes in soil moisture profiles has shown how take-all infection affects the distribution of functional roots (Salt, 1975).

An experiment on barley testing the effect of formalin has been mentioned (p. 29). Formalin not only affected nematodes but also effectively controlled take-all in the year of application. However, in the years immediately following partial sterilisation take-all often became more damaging in treated than untreated soil (Salt, 1971). By contrast there was a beneficial residual effect after fumigation with chloropicrin in the Ley Arable experiment. Chloropicrin applied before planting potatoes increased yields not only of potatoes but also of the following barley, which had little take-all (Dyke, 1974). The reasons why the residual effects of formalin and chloropicrin were different are as yet unexplained but deserve further study.

The number of potato varieties that can be grown at Woburn is limited, partly because so many fields have nematodes, partly because Majestic are often so badly blemished by scab they are unsaleable (see p. 27 for work on chemical control of scab). In addition King Edward and other cultivars susceptible to wart disease, *Synchytrium endobioticum*, cannot be grown because of an outbreak of wart disease in Workhouse Field in 1969. Glynne

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studied wart disease at Rothamsted during 1925–26, and from this work a routine method of testing for the disease was developed, the Glynne–Lemmerzahl method.

During 1892–1911 experiments were made on the control of potato blight by lime-copper sprays (p. 17). This was followed in the 1920s by work at Rothamsted and Woburn which showed that the incidence of the disease, caused by *Phytophthora infestans*, was dependent on the distribution of sources of infection and wind direction rather than manurial treatment and soil type (Kramer, 1930). Between 1950 and 1970 Woburn was one of several locations for a series of experiments on blight. These experiments gave much information on the origin and development of blight attacks, the weather with which they are associated, the factors affecting the field resistance of different potato cultivars, the effects of defoliation on yield and the occurrence of tuber infection and processes leading to it. A system of forecasting likely attacks was developed so that warnings could be given (Hirst, Stedman, Lacey and Hide, 1965).

During the 1960s the market for washed and packaged potatces increased and recently several blemishing diseases have been studied. Infections causing common scab usually occur in dry seasons during the month after stolons begin to swell to form tubers; infection can be prevented by irrigating at this time (Lapwood and Adams, 1973).

Methods for measuring pathogenic fungi on tubers have been developed and used to survey fungal diseases. Experiments at Woburn and elsewhere have shown that tuber pathogens can delay or prevent emergence, decrease yields and change the tuber size distribution within the crop and damage ware crops by blemishing or rotting tubers (Hirst, Hide, Griffith and Stedman, 1970).

Wilting, unilateral chlorosis of leaves and premature death of haulm, has been common in some fields at Woburn. The symptoms are usually associated with the presence of the fungus *Verticillium dahliae* but damage by nematodes and nutritional deficiencies are complications. Rarely has the fungus been isolated from seed tubers and attempts to induce the disease by using infected tubers or inoculating soils have usually failed. Collaborative work with Nematology has shown that *Globodera rostochiensis* and *Pratylenchus neglectus* may aid invasion of potato plants by *V. dahliae*. In experiments testing methyl bromide, aldicarb and benomyl all three treatments controlled both the fungus and the nematodes so that the effect of each pathogen and the interaction between them could not be separated (Hide and Corbett, 1974).

Carrots have often been grown at Woburn with success but occasionally there have been failures. Experiments have shown that carrot motley dwarf virus transmitted by the aphid *Cavariella aegopodii* so weakened young carrot plants that they succumbed to attacks by carrot fly, *Psila rosae*. Systemic insecticides controlled the aphid and substantially increased yields in years when infection of unsprayed controls occurred early (Watson, 1960).

Mann's accounts in the *Rothamsted Reports* of his experiments with crops like soya bean, maize, sweet lupins, Serradella (a species of *Ornithopus*) and Jerusalem artichoke contain observations on the incidence of fungal and virus diseases which may aid those seeking to increase the yields of protein and fodder crops suitable for light soils.

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Soil Microbiology Department

As early as 1896, and as a result of a visit by Voelcker to Germany, the effects of inoculation, which aims to increase legume yields by supplying or increasing the number of nodule-forming bacteria, were tried at Woburn. Most of these early tests showed that materials like 'Nitragin' (1905), 'Nitro Bacterine' (1908) and 'Humogen' (1914) were without effect. Later work concentrated on supplying appropriate and much more effective strains of nodule bacteria. There were experiments on lucerne during 1932–38 and since 1945 several new legume crops have been tried, especially those suitable for light, slightly acid soils. Serradella, sweet lupins and birdsfoot trefoil were all grown successfully immediately after the war. More recently the effects of inoculation of navy beans, *Phaseolus vulgaris*, have been studied at both Woburn and Rothamsted. These last experiments showed the value of having both light and heavy soils of known history and comparable treatment. At Woburn in 1973 inoculation produced early nodulation whilst there was little nodulation on uninoculated plants. Inoculated plants subsequently yielded more than uninoculated. At Rothamsted even inoculated plants were slow to nodulate, all plants showed less vigour than at Woburn and in general there was no response to inoculation and grain yields were much smaller. Because there is increasing interest in growing grain legumes this work is being expanded. Twenty-five varieties of *P. vulgaris* from different countries are currently being tested at Woburn as part of a collaborative project organised by the International Centre for Tropical Agriculture (CIAT) in Columbia.

The problem of 'clover sickness' has already been mentioned (p. 16) and with other departments Soil Microbiology worked on it intermittently between 1931 and 1953. In 1931 some red clover on Stackyard failed and attempts to grow clover again on the same soil gave poor crops. A long series of pot experiments was started to determine the cause of the 'sickness'. By 1936 it was established that clover sickness was something apart from nematode attack although sick plants were often infested with nematodes. Clover sickness could be prevented by very large dressings of FYM but not by giving artificial fertilisers. Heating the soil to 60–70°C for 1–2 h was often temporarily effective but the sickness often returned after one or two further clover crops were grown. Healthy soil could not be inoculated with the disease and a toxic secretion from the clover roots themselves came to be regarded as the probable cause. Studies in the Soil Microbiology Department were directed towards investigating whether the rhizobia causing nodulation were being destroyed or modified by bacteriophage and, later, to a study of fungi in healthy and clover-sick soils. Unfortunately the cause of clover sickness was never satisfactorily explained. Any solution will only come if the problem is tackled by a team of scientists from a number of disciplines all working together.

Recently Woburn soil has been used extensively for work on mycorrhiza. In pot experiments in the glasshouse plant growth responses were often observed after inoculation with *Endogone*.

A study of the changes in populations of *Rhizobium* species (nodule bacteria) in long-term bare fallow on Stackyard was started in 1960 and continued for several years. The numbers of some species declined more rapidly than others. Corresponding data for bare fallow on Highfield at Rothamsted afforded interesting comparisons (Nutman and Ross, 1970).

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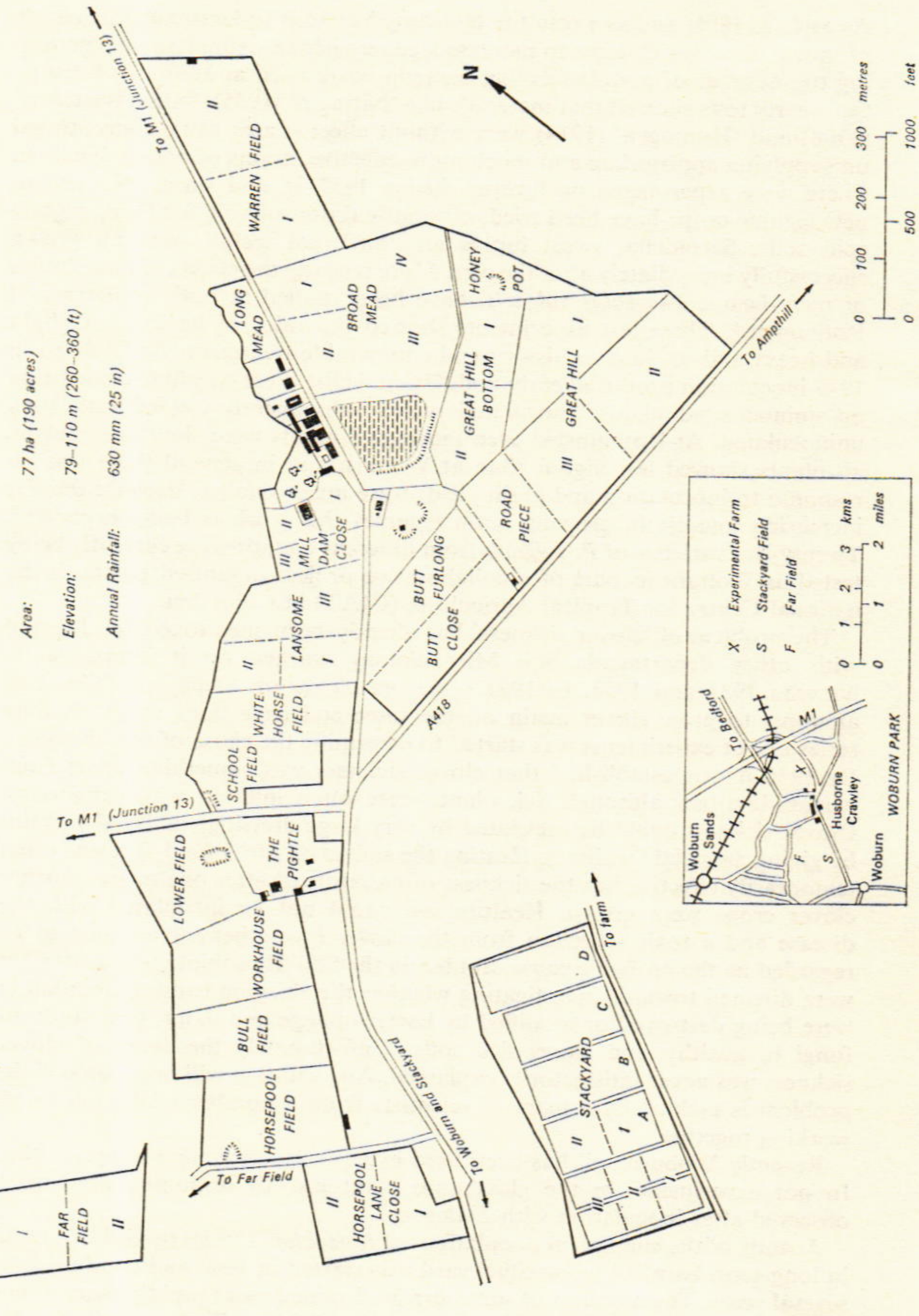
WOBURN EXPERIMENTAL FARM, HUSBORNE CRAWLEY, BEDFORD



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Geology, Soils and Land Use Capability

Geology

Not all the farm's fields have sandy soils on the Lower Greensand (Woburn Sands), some are on clay formations, in particular the Oxford Clay and Chalky Boulder Clay. The junction between the Lower Greensand and the underlying Oxford Clay occurs immediately south of the farm building where it is marked by springs at a height of 84 m O.D. in Mill Dam Close. It then rises north-eastwards to approximately 94 m O.D. on the northern side of Great Hill. Fields to the south and west of the junction are underlain by Lower Greensand, but their soils are not entirely sandy. A superficial cover of Chalky Boulder Clay extends from the south-western side of School Field towards Woburn, and is found on most of the fields west of the Husborne Crawley–Woburn Road, including a small part of Stackyard. This stony clay was deposited by a glacier which invaded eastern England through what is now The Wash during the Anglian glaciation about half a million years ago. Originally thicker and more extensive than it is today, the boulder clay has been eroded from much of the farm by both streams and mass movement of soil. The streams were probably precursors of the Crawley Brook, which now runs roughly parallel with the north west boundary of the Farm. Mass movement of partly frozen soil material occurred in very cold (tundra) conditions, which have prevailed in Britain several times since the Anglian glaciation. The most recent of these cold periods ended about 10 000 years ago and, in most of the soils, development processes, such as weathering, have only occurred since then.

However, even where the boulder clay has been removed and the Lower Greensand is close to the surface, thin slope deposits formed in temperate climatic conditions are widespread; these colluvial deposits are derived partly from the boulder clay and consequently contain more clay and silt than the Greensand. The deposits started to accumulate as a result of downslope movement of soil when the forests were cleared and the soils were first cultivated in the Middle or Late Bronze Age (about 3000 years ago). Much erosion continues today whenever heavy rain falls on soil which has little or no vegetation.

In School Field and others to the south-west, the Chalky Boulder Clay is separated in places from the Lower Greensand by a thin bed of glacial gravel, which has been quarried in several places. The boulder clay is also overlain extensively by a hard, weakly stratified deposit of stony loam or sandy clay, which probably originated as a slope deposit formed from the boulder clay during an intensely cold period.

Small natural lakes previously existed in Mill Dam Close (immediately west of the laboratory) and across the north-western ends of School and White Horse Fields. The silty clays and peats deposited in these lakes overlie the Lower Greensand, and provide further small patches of fine textured soil. However, the areas of both patches have been diminished by encroachment of colluvium washed from adjacent slopes since the lakes were drained and reclaimed.

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Fields to the north of the farm buildings and west of Great Hill are underlain by Oxford Clay, but soils formed directly on this occur only in small areas in Honey Pot Field and Great Hill Bottom II at the foot of Great Hill. This is because in Broad Mead, Long Mead and Warren Fields the clay is overlain by thick deposits of river alluvium, which range in composition from sand or slightly stony sand to silty clay. Also much of the Oxford Clay slope leading down through Great Hill Bottom I towards Broad Mead was buried by a mixture of clay and gravelly sand which issued from the junction of the Lower Greensand and Oxford Clay, just below the summit of Great Hill (in Great Hill I), probably during one of the very cold periods since the Anglian glaciation.

Soils

This complex sequence of deposits gives rise to a greater range of soil types than was recognised previously (Crowther, 1936). Well-drained brown sandy soils with Lower Greensand, often colour-banded, at depths of 25–60 cm (Cottenham series) occur only on the summit of Great Hill, the small hill on the south-western side of Lansome, and parts of Butt Close, Butt Furlong and Stackyard Fields. Elsewhere, especially in the shallow valleys, the Greensand is covered by a variable thickness of colluvium, in which slightly finer textured brown earths (Stackyard series) or imperfectly drained gleyic brown earths (Flitwick series) occur. Table 1 gives the main features of profiles representing these three soils. The colluvium in which all but the lowest horizons of the Stackyard and Flitwick series are developed, contains more clay and silt than the Lower Greensand beneath, and the mineralogical composition of these fractions shows that they are derived mainly from weathered boulder clay (Catt *et al.*, 1975). For example, the main clay minerals in the colluvial horizons are kaolinite, illite and interstratified illite-smectite, an assemblage similar to that in the Chalky Boulder Clay, whereas the clay fractions of the Lower Greensand and of all horizons in the Cottenham profile contain illite and illite-smectite, but no kaolinite. The colluvial subsoil horizons also contain more organic matter than the Lower Greensand, probably because they are largely accumulations of old eroded topsoil.

Because of the larger amounts of silt and clay in the colluvium, Stackyard and Flitwick soils have a larger available water capacity than Cottenham soils. The difference (approximately 30%) can be a critical factor in crop production, especially in very dry summers such as 1976 (Catt *et al.*, 1977). However, the boundaries between the three series are merging and are difficult to map precisely. Lateral movement of finer soil constituents during heavy rain tends to eliminate minor surface irregularities and hollows, such as old ditch or hedge lines, become filled with colluvium to form small areas of Stackyard soils. In some years these differences can be seen as the surface soil dries out in spring and later they become visible as patterns of irregular crop growth. Flitwick series occurs mainly in the lowest, central parts of the valley floors, where the water-table is nearest to the surface; mottling generally occurs within 90 cm of the ground surface, but may be found as close as 40–45 cm where abnormally fine textured subsoil horizons within the colluvium also impede vertical water movement (e.g. the Flitwick profile cited from Lansome Field).

Where the Oxford Clay is not covered by alluvium or other superficial deposits, the soils (Evesham series) are calcareous almost to the surface. Fine

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TABLE 1

Profile data for the three main sandy soil types at Woburn

Profile	Cottenham series, Lansome Field			Stackyard series, Stackyard Field				Flitwick series, Lansome Field				
Horizon depth (cm)	0–22	22–44	44–80	0–24	24–42	42–96	96–180	0–21	21–40	40–119	119–126	172–180
Texture class	Loamy sand	Loamy sand	Sand	Sandy loam	Sandy loam	Sandy loam	Sand	Sandy loam	Sandy loam	Sandy loam	Clay loam	Sand
Clay % (<2 μm)	10	8	5	11	10	8	6	12	17	12	21	10
Silt % (2–60 μm)	9	8	5	18	20	19	4	15	21	24	33	3
Fine sand % (60–250 μm)	66	72	82	50	48	52	80	50	43	48	34	74
Coarse sand % (250–2000 μm)	15	12	8	21	22	21	10	23	19	16	12	13
Colour	Dark brown	Brown	Olive and yellowish red bands	Dark brown	Brown	Yellowish brown	Olive, yellowish brown and yellowish red bands	Dark brown	Reddish brown	Reddish brown and grey mottles	Very dark grey	Grey and brown mottles
Organic carbon %	2·05	0·58	0·15	1·85[1]	0·47	0·30	0·06	2·07	0·75	0·57	0·62	0·07
pH	7·2	7·3	7·1	7·1	7·2	6·9	6·9	7·0	7·4	7·0	6·9	6·8

[1] % C is much larger than in many soils on Stackyard probably because the sample was taken from a track long under grass.

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rusty mottles in the well-structured surface horizon together with predominantly grey or olive subsoil colours indicate imperfect to poor drainage. The soils on alluvium (Woburn series) and lacustrine deposits (Ridgmont series) are also poorly drained, but are non-calcareous, weakly structured and often coarser in texture than the Evesham series. The soils associated with Chalky Boulder Clay *in situ* are more stony than others on the farm; most are imperfectly drained (Husborne series), with upper horizons formed in the periglacial slope deposit overlying the boulder clay, but there are small patches of slightly better drained profiles (Pightle series). The calcareous boulder clay is usually more than 1 m below the surface, and never closer than 40 cm.

Potassium in the soils

The Lower Greensand is so named on account of the local occurrence in the deposit of the green mineral glauconite. This contains approximately 7% K, and is often considered an important potassium supplying mineral in greensand soils. Crowther (1936) suggested that potassium supplied by glauconite explained the lack of crop response to applied potassium at Woburn.

Most of the glauconite in the Lower Greensand of Bedfordshire and in the farm soils occurs as sand-sized pellets. These pellets are only a minor constituent, about 1%, of the total sand and are too few to give it a green colour. However, large blocks of bright green sandstone found on White Horse Field suggest that originally the sand may have been green. In these blocks a thin glauconite coating on other sand grains (mainly quartz) has been preserved by intergranular deposition of silica, probably soon after the sands were laid down under the seas of the early Cretaceous period. The glauconite coatings in unsilicified parts of the sands have been oxidised to a mixture of iron oxides, illite and illite-smectite. In the Cottenham series, the illite in these coatings is the main natural source of potassium, but in other soils illite derived from the Chalky Boulder Clay, which does not occur in grain coatings, is more important. The relatively rare glauconite pellets in the soils supply little or no potassium to crops. The lack of response to applied K noted by Crowther was probably due to the fact that the clay illite could supply enough potassium for the small crops grown at the time. Since nitrogen dressings have been increased, yields have been larger, and responses to applied potassium are now common.

Land use capability

A system of classifying soils based on their capability and adaptability for agricultural crops has been described by Bibby and Mackney (1969). The classification aims to indicate the potential of land under reasonably good management, and when published in map form is usually related to a detailed Soil Survey map. The system is not based on current land use, and limitations which can be removed or decreased at an acceptable cost are not allowed for. Capability subclasses are based on limitations affecting land use, such as wetness, texture, slope and climate.

Seven classes, numbered 1 to 7, are used. The following abbreviated descriptions of the first three are taken from Bibby and Mackney. Class 1 is land with very minor or no physical limitation to use; amongst other things it is land with good reserves of moisture or with suitable access for roots to

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moisture. Class 2 is land with minor limitations that decrease the choice of crops or interfere with cultivations; limitations include slightly unfavourable climate and soil texture and structure. Class 3 is land with moderate limitations that restrict the choice of crops and/or demand careful management.

D. J. Eagle of ADAS (Eastern Region, Cambridge) recently surveyed a number of fields and experiments, and classified them according to this system. The results can be related to the soil series described above, which have been mapped over part of the farm by Catt *et al.* (1975, 1977). The Cottenham series, as examined on block 1 of the Ley Arable experiment (Stackyard), part of the Organic Manuring experiment (Stackyard), Series 1 of the Market Garden experiment (Lansome), the Irrigation experiment (Butt Close) and on parts of Butt Furlong, is poor class 2. However, in eroded sites, such as the summit of Great Hill, where the Lower Greensand is immediately beneath the plough layer and the soils are slightly more susceptible to drought, the Cottenham series is class 3. The Stackyard and Flitwick series are both good class 2 soils, mainly because they have a greater available water capacity and suffer less from drought than any of the Cottenham soils. Stackyard series occurs on the Long Term Liming experiment and part of the Organic Manuring experiment (Stackyard), and on Series 2 of the Market Garden experiment (Lansome). Flitwick series was examined on lower blocks of the Ley Arable experiment (Stackyard). Finally, two of the heavier soils on the farm, the Ridgmont series in Mill Dam Close and the Woburn series on Warren Field, were grouped as class 3, because their large clay content and poor drainage make the timing of cultivations more critical than on the lighter soils.

As many of the experiments were laid out before the differences between soil types were recognised, they often straddle soil boundaries and include two or more soil series with different capabilities. This has often complicated the interpretation of experimental results. However, careful examination of past results from plots on different soil series does offer the opportunity of studying yield differences in relation to soil type and should make it possible to define the capabilities of the different series in greater detail. Also, it is important that new experiments should be sited in relation to the soil boundaries, so that each block is on one soil series only.

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During 1878–1921 annual reports were published in most years in the *Journal of the Royal Agricultural Society*. Since 1922 accounts of each year's work have appeared in the *Rothamsted Report*. A number of review articles especially those by J. A. Voelcker (1923) and E. J. Russell and J. A. Voelcker (1936) are referred to in the text. The frontispiece and Plates 3 and 4 are taken from Russell and Voelcker (1936) and Plates 1 and 2 from the *RASE Journal*, 1897.

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CONVERSION FACTORS

Factors for the Conversion of Imperial to Metric Units

1 inch (in.)	= 2·540 centimetres (cm)
1 foot (ft) (=12 in.)	= 30·48 cm
1 yard (yd) (=3 ft)	= 0·9144 metre (m)
1 square yard (yd^2)	= 0·8361 m^2
1 acre (ac) (=4840 yd^2)	= 0·4047 hectare (ha)
1 ounce (oz)	= 28·35 grams (g)
1 pound (lb)	= 0·4536 kilogram (kg)
1 hundredweight (cwt) (=112 lb)	= 50·80 kg
1 ton (=2240 lb)	= 1016 kg = 1·016 metric tons (tonnes) (t)
1 pint	= 0·5682 litre (l)
1 gallon (gal) (=8 pints)	= 4·546 litres
1 fluid ounce = 1/20 pint	= 0·02841 litre = 28·41 ml
1 cubic foot	= 28·32 litres

To convert	*Multiply by*
oz ac^{-1} to g ha^{-1}	70·06
lb ac^{-1} to kg ha^{-1}	1·121
cwt ac^{-1} to kg ha^{-1}	125·5
cwt ac^{-1} to t ha^{-1}	0·1255
ton ac^{-1} to kg ha^{-1}	2511
ton ac^{-1} to t ha^{-1}	2·511
gal ac^{-1} to l ha^{-1}	11·233

The following factors are accurate to about 2 parts in 100:

1 lb ac^{-1} = 1·1 kg ha^{-1}

1 gal ac^{-1} = 11 litres ha^{-1}

1 ton ac^{-1} = 2·5 t ha^{-1}

In general reading of the text there will be no great inaccuracy in regarding:

1 lb = 0·5 kg

1 lb ac^{-1} = 1 kg ha^{-1}

Temperatures

To convert °F into °C subtract 32 and multiply by $\frac{5}{9}$ (0.556)

To convert °C into °F multiply by $\frac{9}{5}$ (1·8) and add 32

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