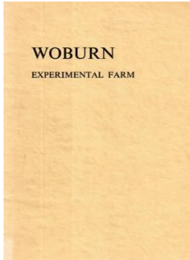
ROTHAMSTED RESEARCH

Woburn Experimental Farm



Full Table of Content

Recent Experiments

Rothamsted Research

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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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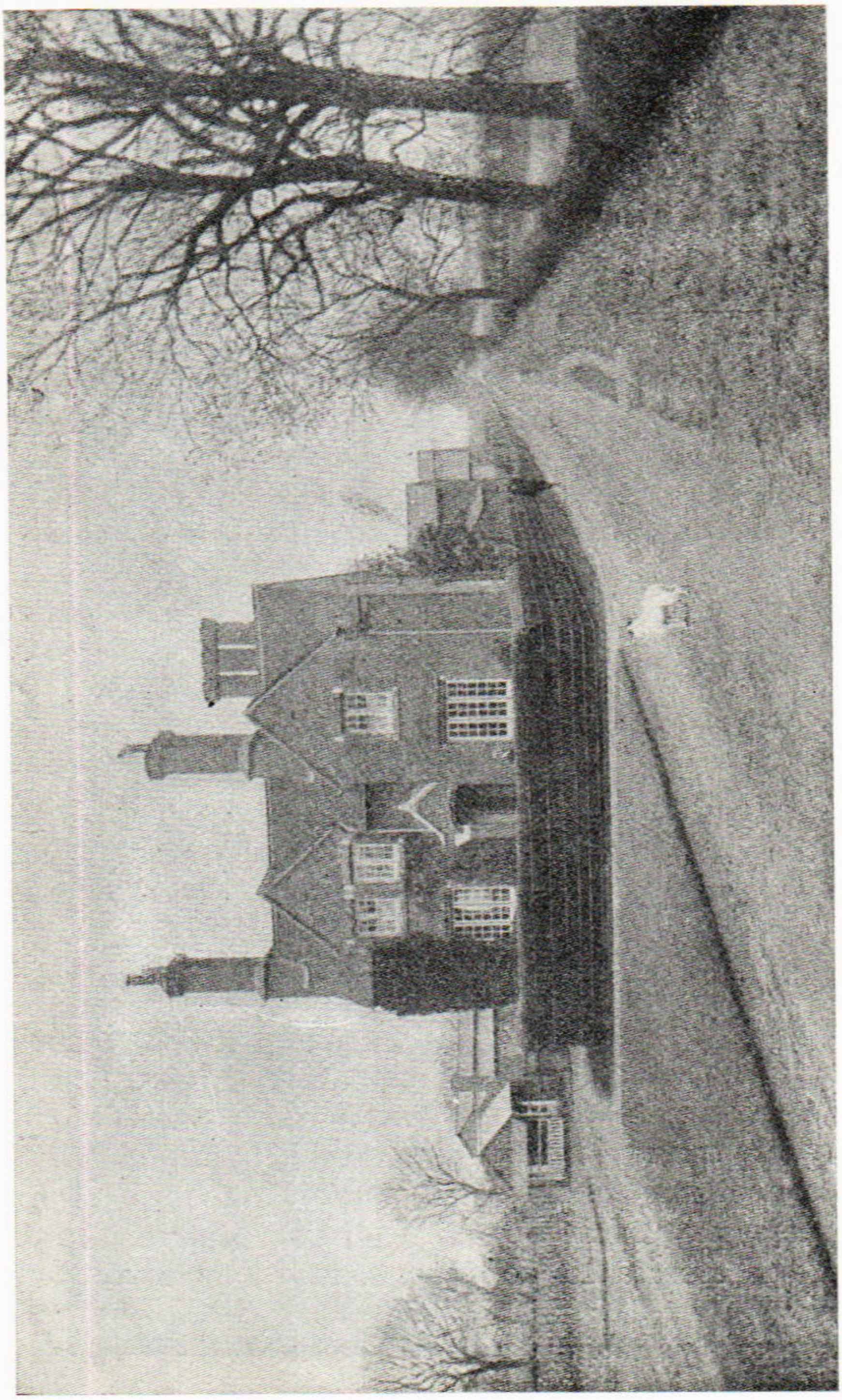
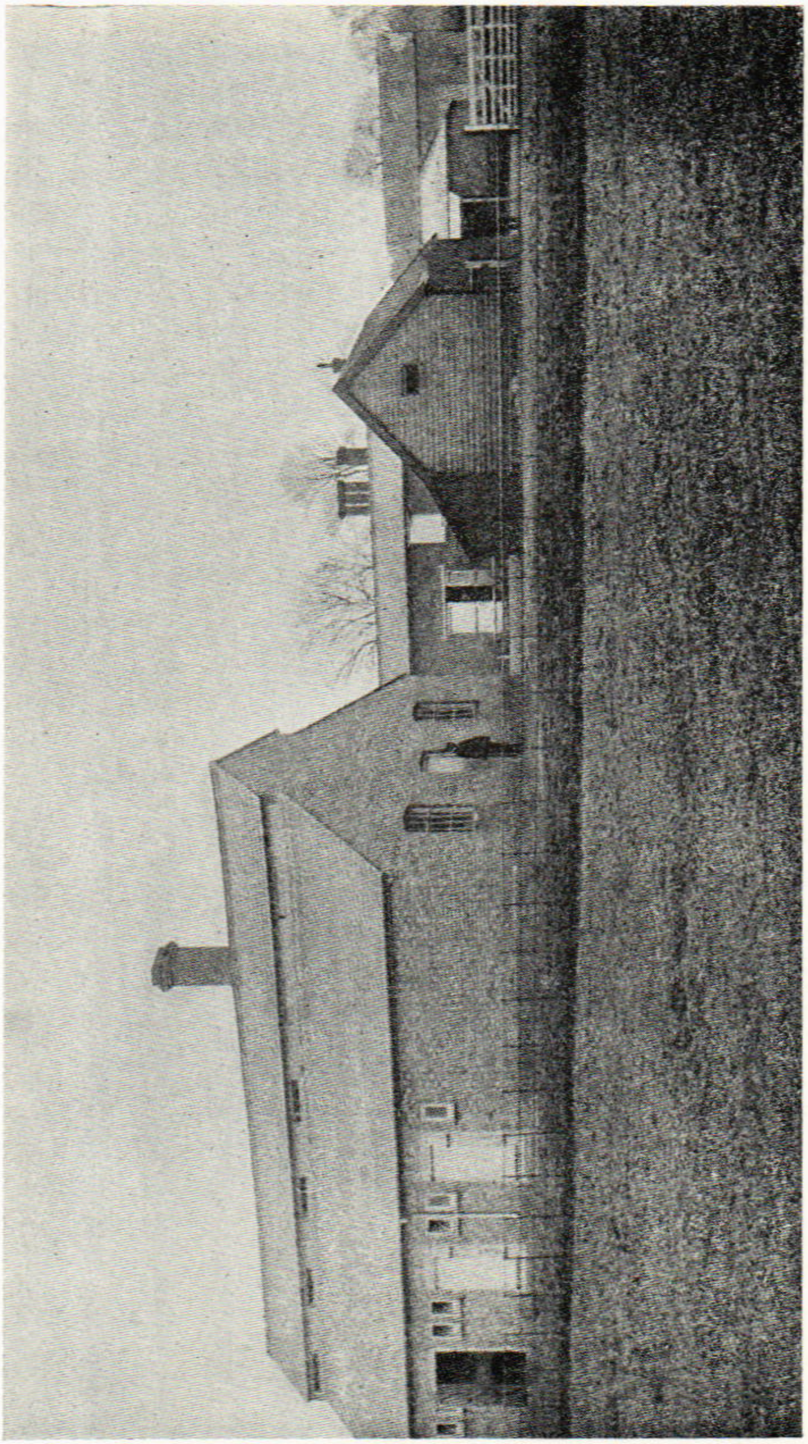
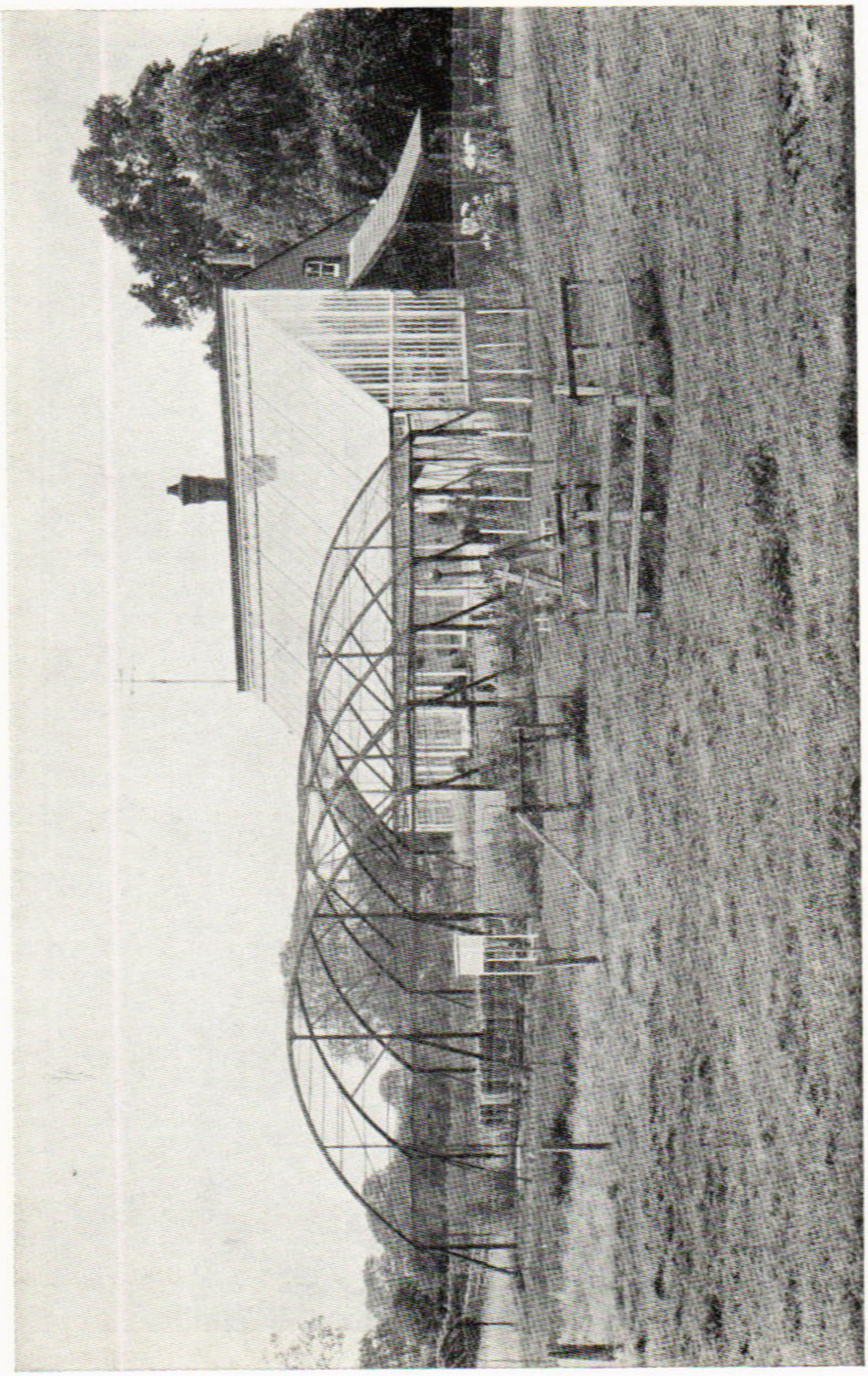


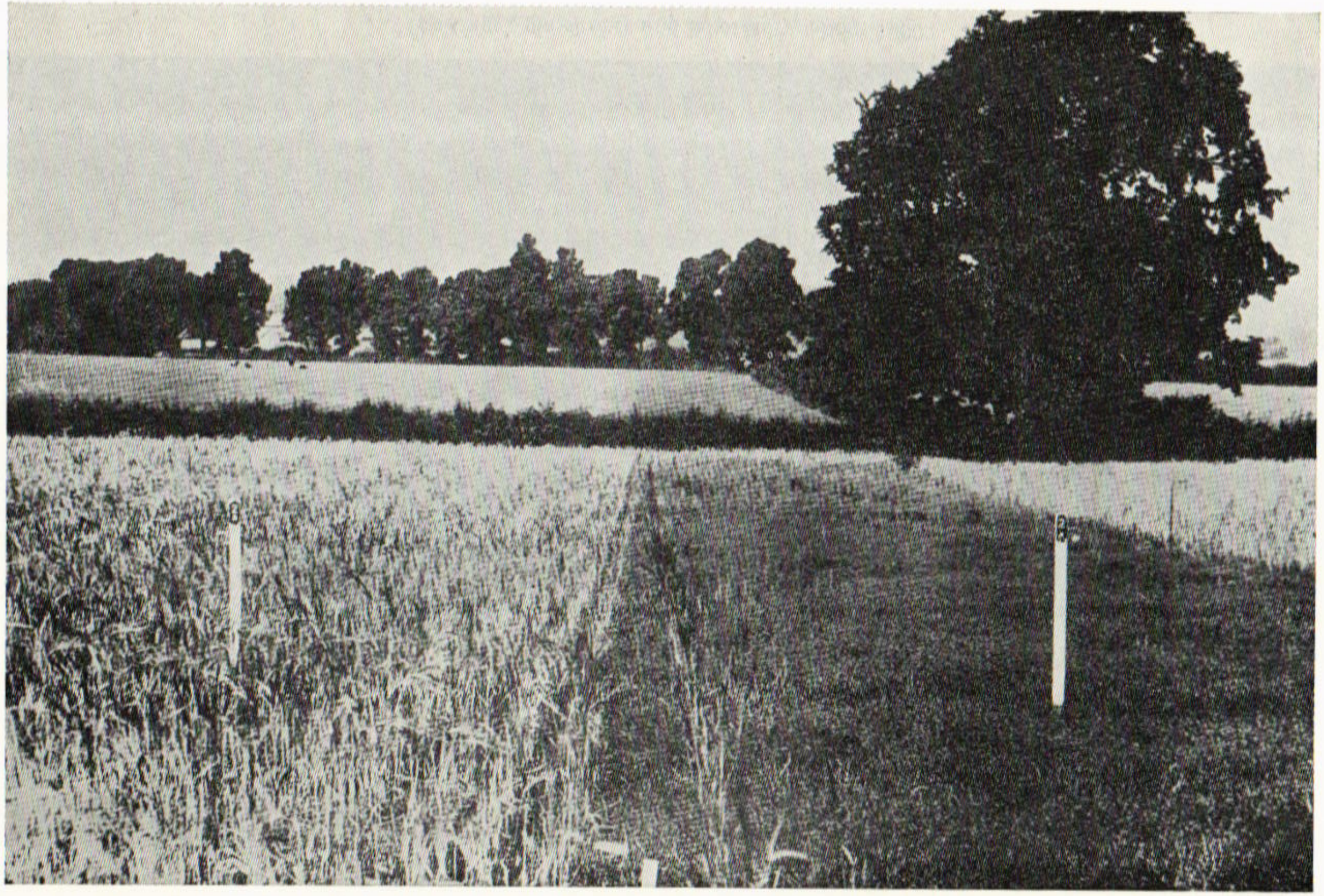
The farm house about 1890



Building containing the feeding boxes erected 1876



'The Cage', glasshouse and laboratory, about 1900



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,

https://doi.org/10.23637/ERADOC-1-153

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

https://doi.org/10.23637/ERADOC-1-153

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 potatoes 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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