ROTHAMSTED RESEARCH

Rothamsted Experimental Station Guide

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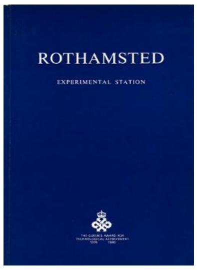

Rothamsted Experiment Station Guide

Rothamsted Research

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ROTHAMSTED

EXPERIMENTAL STATION

THE QUEEN'S AWARD FOR
TECHNOLOGICAL ACHIEVEMENT
1976 1980

The presentation of the Queen's Award for Technological Achievement on 3 July 1980. Left to right Mr E. Lester, Deputy Director, Dr L. Fowden, Director, Major General Sir George Burns, Lord Lieutenant of Hertfordshire, Lord De Ramsey, Chairman of the Lawes Agricultural Trust Committee, Dr M. Elliott, Deputy Director and Head of the Department of Insecticides and Fungicides. This is the second Queen's Award earned by Rothamsted in respect of the range of pyrethroid insecticides developed by members of the Department of Insecticides and Fungicides.

Photo: Herts Advertiser

ROTHAMSTED

EXPERIMENTAL STATION

GUIDE

1981

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INTRODUCTION

Rothamsted Experimental Station, founded in 1843 by John Bennet Lawes, is the oldest agricultural research station in the world and one of the largest, with a total staff of about 800. It is situated on the Rothamsted estate, where its founder was born in 1814. The magnificent old Manor House had been the home of Lawes's ancestors for 200 years. Now it is used as a residential hostel for members of staff and visiting workers.

As a young man Lawes was aware of food shortages and widespread poverty in England following early industrialisation and foresaw the need to raise the general level of agricultural practice. He had acquired a deep interest in chemistry and, in 1842, he patented a new method for producing superphosphate and started the Lawes Chemical Company to manufacture this and other 'manures'. In the following year he engaged the services of J. H. Gilbert, a chemist of similar age, and together they developed field experiments to relate crop growth to the chemical composition and manurial treatment of soil. This collaboration lasted 57 years and established many of the present concepts of plant nutrition. Wheat was used in the first experiment, laid down on Broadbalk field, and experiments with barley, root crops and permanent grass followed on other fields of the home farm. All still continue with small modifications and form the basis of the 'Rothamsted Classical Experiments'. They are now supplemented by many annual and some newer long-term experiments.

For long the Station was financed wholly by Lawes, at first directly but after 1889 from a benefaction of £100 000 placed under the stewardship of the Lawes Agricultural Trust Committee who became the Station's Governing Body. The Trust Committee members are appointed by the Royal Society of London, the Royal Agricultural Society of England, the Royal Society of Chemistry, formerly the Chemical Society, and the Linnean Society. Research was supported entirely by the Trust fund until 1911, but from that year the work has depended increasingly on support from public funds and now is largely financed by annual grants from the Agricultural Research Council.

Lawes died in 1900, and during this century there has been a steady increase in the number of scientists working at Rothamsted. The Station's research, at first mainly chemical, is now much broader and involves almost all scientific disciplines applicable to crop improvement, except traditional plant breeding. This range of work is divided amongst the departments whose programmes are outlined briefly in this booklet. The Field Experiments Section acts as co-ordinator between the departments and the Farm in the conduct of field experiments and is also responsible for dealing with visitors. Rothamsted is also the headquarters of the Soil Survey of England and Wales and houses the Commonwealth Bureau of Soils.

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Broom's Barn Experimental Station in Suffolk, a department of Rothamsted Experimental Station, is responsible for much of the research effort on sugar beet. The work is financed by the Ministry of Agriculture's Sugar Beet Research and Education Committee (SBREC). In 1959 the Lawes Agricultural Trust Committee bought Broom's Barn Farm (73 ha) with money granted by SBREC and built the present laboratories; the work previously done at the Dunholme Field Station was transferred there in 1962.

The Rothamsted estate extends to 330 hectares (813 acres), a small proportion of which carries woodlands. About half the land is suitable for field experiments. The Lawes Agricultural Trust Committee is also responsible for the Woburn Experimental Station (76 ha) in Bedfordshire, and the small Saxmundham Experimental Station in Suffolk.

Rothamsted's role is entirely in research; it does not teach formal undergraduate courses in agricultural science. However, suitably qualified people can undertake postgraduate research at Rothamsted under schemes which allow them to register for higher degrees at London or certain other Universities.

This booklet presents a brief account of the laboratory-based research; short descriptions of the work of each scientific department appear in the early pages of this new version. A few of the long-term experiments at Rothamsted are described in detail and there are sections on the soil and cropping of the Rothamsted Farm. More detailed information about the work and results appears in Annual Reports of the Station, obtainable from the Librarian. A list of other Station publications is given on page 71.

The Staff List, Plan of Station, and up-to-date information on the work of the departments and changes in the field experiments occurring since this booklet was printed are to be found in the pocket of the back cover.

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WORK OF THE DEPARTMENTS

BIOCHEMISTRY DEPARTMENT

The department is concerned almost entirely with laboratory work. However, this work is related to two of the major problems confronting world agriculture in the field. Recently the department has been asked to increase its research effort on seed protein genes and to start a programme on protoplast regeneration as part of the ARC's priority programme on the genetic manipulation of crop plants.

The biochemistry of virus infected plants. There is a considerable amount of sophisticated information on the structure of plant viruses and on aspects of their replication. In contrast very little is known about some basic processes such as the initial stages of infection of a plant cell, or the reactions in infected plants that either limit the systemic spread of a virus, or lead to virus destruction. We study these processes because when we understand them, we may be able to contol and exploit them.

Some virus infections lead to a localised and often necrotic response, in which the virus does not spread much beyond the infection zone. The processes that restrict the virus also seem to induce in the plant a resistance to further infection. One of the most obvious biochemical consequences of this type of infection is the production of a family of novel proteins, the pathogenesis-related (PR) proteins, both in inoculated and in neighbouring leaves. In collaboration with other departments we are studying the PR-proteins produced when tobacco plants are infected with tobacco mosaic virus (TMV) to determine if they have a role in virus-localisation or in inducing resistance. We have partially characterised three of the proteins, and demonstrated their presence in tissue cultures where viruses are known to replicate poorly. The production of the proteins in tobacco leaves can be induced by some chemicals and this will facilitate detailed investigations into the mechanism that controls their synthesis.

A reaction that might lead to the destruction of viruses in senescing infected leaves is their reaction with the o-quinones produced during the enzymic oxidation of leaf phenols. This idea has been tested using potato virus X (PVX) whose products after reaction with *o*-chlorogenoquinone have been characterised. No evidence was found that the reaction occurs naturally with a common strain of PVX, nor that it could explain the natural persistence of some strains of PVX compared to others. Paradoxically, information gained of the structure of PVX suggests that it is a good subject to use in a search for the putative receptor sites of leaves at which infection is thought to be initiated.

Factors affecting the quality of plant proteins. A large proportion of plant proteins has to be imported into this country. In part this is related to the quality of home-produced proteins; cereal seed proteins generally are low in lysine, which limits their nutritional value for feeding the non-ruminant

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animals, and they have to be supplemented with other protein feedingstuffs; legume seed proteins, in contrast, are deficient in the sulphur amino acids, methionine and cysteine. The protein content, and in some cases its quality, of home-grown wheats determine the proportion that can be used for baking; any improvements in either of these factors would increase the proportion of British wheat that could be used. The department is concerned with some aspects of these problems.

The metabolism of nitrogen in plants. We are studying the assimilation of nitrogen available to crop plants, either from the soil or from nodule fixation, into amino acids and its subsequent transfer to the seed. Particular attention is paid to understanding those parts of the process that have not so far been fully described in biochemical terms. We are also investigating the effects of nitrogen and sulphur fertilisers on the composition of seed proteins.

The synthesis of amino acids. Although amino acid biosynthesis has been well studied in bacteria, far less is known of the enzymology of the process in plants. We are concerned with the isolation and characterisation from crop plants of the enzymes involved in the synthesis of lysine, methionine and threonine. We are also studying the regulation of these synthetic reactions. It is known that once an organism has sufficient of a compound for its own needs it tends to prevent waste by shutting off further synthesis. These feedback controls have been studied in bacteria and animals and have also been shown to operate in plants. They have particular relevance in this problem in that they limit the production of agriculturally desirable compounds. The nature of the feedback controls as they relate to lysine, methionine and other amino acids is being investigated and mutants of barley that have relaxed feedback controls and which contain enhanced levels of soluble threonine in the grain have been selected.

Factors affecting the synthesis of storage proteins. We have initiated a programme of work on the basic biology of cereal seed protein synthesis. The aim is to understand the genetic, biochemical and environmental factors regulating storage protein synthesis. Initial work has concentrated on barley and is related to the fact that nutritional improvement of seed proteins can be brought about by changes in the proportion of the different component proteins. We are investigating the changes that are brought about by high-lysine mutations particularly in the compostition of the storage proteins and in the developmental sequences that occur during seed maturation. Further work encompasses wheat proteins and the relationship of their various properties to baking quality. We have also studied the chromosomal location of the structural genes controlling the storage proteins. Our knowledge has enabled us to devise means of varietal identification of cereals grains. The physical isolation of the storage protein genes is at present being undertaken with a view to their eventual modification and reintroduction into crop plants.

Protoplast regeneration. Protoplasts are potential recipients for the introduction of new genetic information outside the normal sexual methods. These cells, which have had their walls removed, can take up nucleic acids, organelles or even fuse with protoplasts of different species relatively easily. Protoplasts from certain species also have the capacity to regenerate whole

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plants and to express the information introduced at the protoplast stage; thus for example workers elsewhere have fused protoplasts of potato and tomato and regenerated hybrid plants. Our aim is to develop techniques for the growth of isolated protoplasts of crop plants, which so far has proved difficult or impossible according to species. Currently we are concentrating on wheat, barley, potatoes and rapeseed. The work consists of three major parts:

1. The establishment and propagation of plants under controlled growth chamber conditions. The initiation and propagation of morphogenetic tissue cultures and shoot cultures.
2. Isolation, culture and growth of protoplasts obtained from all the sources listed in (1).
3. Plant regeneration from protoplast derived calluses. Re-establishment of plants in growth chambers.

BOTANY DEPARTMENT

Most of the department's work consists of the study of the physiology of crop plants to discover how crop yield depends on the progressive growth and development of individual plants. The practical objective is to define a rational basis for increasing crop yield either by changes in cultural methods or by the definition of selection criteria in the breeding of new varieties.

Factors controlling grain yield in cereals. Grain yield is determined by the surface area and duration of the green parts of the plant after anthesis (flowering) and by the capacity of the ear to store photosynthate. The effects of nitrogen fertiliser, irrigation, seasonal weather variations and cultural practices are studied in relation to the grain yield of wheat. In addition the size and activity of the root system, particularly in relation to soil water use and the absorption of nutrient ions, are being studied.

The measurement of photosynthesis, respiration and the distribution of assimilate. The influence of nitrogen supply and plant density on the carbohydrate metabolism of varieties of both spring and winter wheat is being studied. Gas exchange is determined using an infra-red gas analyser which can be used both in the field and the laboratory. The loss of carbon dioxide by the processes of dark respiration and photorespiration is studied together with the distribution within the plant of the photosynthate that is retained.

The mechanism of photosynthesis and of photorespiration. It is important to establish how far yields of arable crops are related to the photosynthetic capacity of the crop. The photosynthetic capacity depends on a number of processes and a detailed biochemical investigation is made of those considered most likely to regulate the overall process. The enzyme concerned with the uptake of carbon dioxide (RuBP carboxylase) has been purified from different crop plants and its main catalytic properties investigated; it also catalyses the uptake of oxygen and thus initiates the photorespiratory cycle. Plants native to temperate climates lose some 30% of their photosynthetic products immediately as carbon dioxide through the process of photorespiration. The enzymes concerned in the photorespiratory oxidative cycle have been studied

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and the possibility of regulation examined. At temperatures of 20°C stopping photorespiration could result in yield increases in excess of 50%; at lower temperatures the benefit will be smaller but still significant.

Water relations of cereals and sugar beet. Growth of plants and their agricultural yield decrease as the water deficit in soil and plant increases. For cereals and sugar beet both in artificial environments and the field, the physical factors in soil, plant and atmosphere which control the supply of water to and loss from the plant have been investigated. Growth and yield are related to components of the tissue water balance. The ways in which water deficits decrease photosynthesis and alter metabolism are investigated. In plants producing three-carbon compounds as primary photosynthetic products, stomatal closure is initially of greatest importance but more severe water deficits damage the photosynthetic apparatus. Photorespiration remains large and causes loss of newly assimilated and stored carbon. In contrast plants such as maize, which form four-carbon organic acids as primary fixation products, lose much less carbon by photorespiration over a range of water deficits.

Growth substances in wheat and sugar beet. The different stages of development of the wheat grain, e.g. cell wall formation and cell division, cell expansion, starch filling, and water loss and ripening, are studied, in relation to the regulation of these stages by external factors and the involvement of endogenous growth substances. With sugar beet, the role of both endogenous growth substances and synthetic growth regulators is examined in the growth of leaves early in the season, in the growth of the storage root and also in bolting.

Factors controlling leaf growth and sugar accumulation in sugar beet. The yield of sugar from sugar beet is related not only to the extent to which roots grow but also their ability to accumulate large concentrations of sugar. The environmental and internal factors which control plant growth have been investigated. Plant dry matter and the amount of sugar present in the root are largely determined by environmental conditions particularly those affecting the early development of the leaf canopy. By contrast, sugar concentration in the storage root is determined more by internal processes which modify the anatomical structure of the root and the sizes of its constituent cells.

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BROOM'S BARN EXPERIMENTAL STATION*

The research of the Station is organised in four multi-disciplinary groups which deal with major topics of concern to the sugar beet industry.

Plant establishment. Research at Broom's Barn indicates that inadequate seedling establishment, exacerbated by the present practice of drilling-to-stand, decreases yields by 10% nationally. Many factors are involved, some also slowing early growth, and the main research is on seedling pests and diseases and their control, seed quality studies, and an investigation of the physical and chemical conditions of seedbeds.

Environmental and nutritional aspects of crop growth and productivity. The group, co-operating closely with staff of the Botany Department, aims to define principles governing growth and yield, and has already shown that both are directly proportional to the amount of solar radiation intercepted when the crop is not affected by drought, disease or pests. It has also found that dry matter production is directly related to the amount of water used. The validity of these principles is being explored by examining the crop's response to current recommendations for irrigation, nitrogen fertiliser and plant density, and by growing crops in South Wales where radiation receipts are significantly larger. The group is also engaged in a co-operative programme of fertiliser experiments with British Sugar and in studies of herbicides and weed competition and the relationship between bolting and environment. The collection and reporting of weather records from the agrometeorological station are the responsibility of the group.

Diseases and pests. Virus yellows is the most damaging sugar-beet disease but current control measures are only partially effective and need improving. In order to be able to improve our advice on controlling the disease, the work of the group seeks to increase our knowledge of: the two distinct viruses that make up the 'virus yellows' complex, their effect on the plant and their epidemiology; the biology of the aphids that carry the viruses, and their interaction with predators and the physiology of the beet plant; controlling the spread of the disease within crops despite increasing insecticide resistance in the aphids.

Recent research has shown that controlling powdery mildew in sugar beet can be profitable and collaborative experiments with British Sugar continue in order to show where and when treatment is justified.

Rotational problems. Weed beet has become a serious problem because of seed shed from bolters in early sown crops and because some hybrid seed crops grown in southern Europe have been contaminated with wind-borne annual pollen. At least one quarter of the land growing sugar beet is now infested. We are seeking an understanding of the population dynamics of the weed over the whole rotation.

A research effort concentrating on beet cyst-nematode investigates the relationship between populations, season, crop rotations and yield loss, and work is planned on alternatives to rotation for control.

* Those wishing to visit Broom's Barn or who require further information should apply to the Head of Station, Broom's Barn Experimental Station, Higham, Bury St Edmunds, Suffolk. *Phone* (0284) 810363.

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It has long been recognised that beet grow slowly on chalkland until late summer; a research programme continues to investigate the growth responses which have been shown to follow soil sterilisation.

In addition to the research programme carried out at Broom's Barn and on grower's farms, the 50 staff provide an important educational and advisory service to the sugar-beet industry, lecturing at meetings, advising on problem fields and on cultivation and disease control problems, organising and speaking at refresher courses for other sugar beet industry workers, co-operating in crop surveys and seed crop certification schemes, exhibiting at demonstrations, etc.

COMPUTER DEPARTMENT

Early computing. Computing has been one of the most rapidly developing sciences and technologies over the past three decades. By any measure of power, capacity, theoretical and practical developments, training, resources and the range of activities, there has been a transformation in the scene between the introduction of the prototype thermionic valve computer—the NRDC Elliott 401—in the Statistics Department in 1954, and the additional ICL 4-72, installed in 1977. Between these two events there was the installation of a production version of the prototype—Elliott 402E—in 1957, followed by the transistorised Ferranti Orion in 1964, which was replaced by the English Electric integrated circuit System 4-70 in 1970. Such a roll call of different British computer manufacturers will never be repeated as all are encompassed in the single major UK company, International Computers Ltd—ICL.

Because of their speed and ability to repeat cycles of calculations, the earliest computers were applied only to numerical problems. This indeed was the position at Rothamsted, where the first computer was exclusively used for statistical computation (and this remains one of the cornerstone activities even today). Experience with the development of programs, particularly for routine statistical computation, revealed the flexibility of the computer to embrace other organisational aspects of the job, and that the more effective programs dealt with more than the calculation aspect of the problems.

As such programs became available, other institutes began to submit their data for analysis, first by having their data prepared here, but later at their own institutes. Input data on paper tape or cards, and the printed output results, were exchanged through the postal services. Under this experience, workers at the institutes became more interested in developing their own programs but were frustrated by turnaround delays in the postal service. This was eased temporarily for the major institutes by the Telex system. This experience clearly pointed to the need for and the benefits of better data communications between the institutes and Rothamsted.

Present computing. By the mid-1960s, the major objectives of a centralised computing service were more clearly identified, and included:

(a) means for connecting a variety of terminals at institutes into Rothamsted;
(b) methods of storing and identifying data in a form easily and selectively accessible to users;

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(c) a program to manage the dynamic interplay between the demands for the assignment and release of resources, and action on error conditions;
(d) general purpose program utilities to ease the programming problems, to broaden the range of problems which could be tackled, as well as improve the opportunities for the exchange of such programs with other computer centres.

Both the hardware and software techniques to meet these aims were already under development when, in 1968, the System 4-70 was chosen. The company provided the basic system, known at Multijob, which would enable users to set up, interrogate and control their work at a distance with reasonably convenient procedure for storing and retrieving data as files within a central filing system. The well-established general purpose programming language, FORTRAN, became the main programming tool. This was the basic on which the multiaccess service was inaugurated in 1971 and which currently supports some 150 terminals including teletypes, video displays, fast printers and batch terminals at most ARC-supported research Institutes in England and Wales.

Developments. In common with most major scientific computing sites, it was soon realised that this department would have to undertake its own development programme in order to provide users with the most effective service for their needs. These efforts have ranged from fairly simple modifications to improve the performance of the system under our demand pattern to the provision of additional facilities either as alternatives or additions to company proposals.

One of the more important of these was the decision to replace a fixed hardware link between the user terminal network and the central computing facility by a programmable communications processor. When this is completed all present and future development and investment in the network could then be sustained independently of changes in the central system, thus maintaining the maximum flexibility for the user within the constraints of a public procurement policy on large computer systems.

The overall effect of these developments and the marked improvement in the reliability of the basic software and hardware has been to stimulate the demand by users and there was ample evidence that serious bottlenecks were likely to affect the service. To overcome these the central configuration has been enhanced by an additional ICL System 4-72 which is coupled to the 4-70 to provide the broadest base for an extended multiaccess service. This was a major development task and undertaken jointly with ICL at Rothamsted. Meanwhile, the range of programming languages has been extended to include BASIC, a neat language particularly for dealing with 'one off' calculations, and COBOL, an internationally accepted language for management services problems. Other more specialised languages dealing with simulation, model building, plotting and information retrieval are also available on the service. Details can be obtained from the department.

Future computing. The present dual System 4 configuration has satisfied most user needs up to the present but a replacement system is planned to be in service by the early 1980s. The nature of this service will take account of the

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growing user experiences and some of the more technological developments such as:

(a) interactive computing where a user can expect a prompt response to any service demand;
(b) the influence of massive on-line data storage devices on shared databases;
(c) the impact of low cost micro-processor technology on terminal and other instrumentation design;
(d) the direct data capture and analysis of instrumented experiments;
(e) the increasing speed and flexibility of data communication;
(f) the technical possibilities for economic resource sharing between computer centres and others.

These are only a selection, but confirm that there is no slackening in the rate of technological change, and there is every expectation that the future will be as stimulating as the past. It is a great encouragement to the department that the users continue to demand an expanded service because their involvement remains the best indication of the importance of the computing service to agricultural research at the research, support and management levels.

The System 4 replacement is being considered and the outcome will appear in a supplementary report in the pocket of the back cover of this Guide.

ENTOMOLOGY DEPARTMENT

The approach to agricultural entomology in this department is essentially long-termed based on an understanding of the responses of insects to their environment, including the weather, their habitat, food and other animals and pathogens. Ways in which insect numbers are modified by these factors are investigated. Direct methods of control by insecticides are studied jointly with other departments. The work includes ecological studies aimed at establishing the underlying causes of population changes, examination of novel methods of pest control, and of the environmental effects arising from current pest control practices. The possible development of new pest problems is constantly reviewed. Work is primarily on insects, but also extends to mites, earthworms and slugs.

Basic ecology. Before effective pest control measures can be devised much information is needed; for example, the identity of pests involved, their origin and regional and local distribution, their abundance and the factors influencing it. Much of the work is concerned with these problems.

Monitoring airborne pests with traps. Aphids are very serious insect pests in Great Britain, causing direct damage and transmitting virus diseases to many crops. In an effort to give early warning of infestations so that pesticides can be applied at the correct time, a monitoring system has been established by the Rothamsted Insect Survey. Twenty suction traps, like the one sampling at a height of 12.2 m (40 ft) near the Meteorological Enclosure on Rothamsted Farm, are sited throughout Britain and daily samples of insects are identified. The resulting information on their distribution is published in a weekly

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Bulletin, which is widely distributed to members of the Agricultural Development and Advisory Service of the Ministry of Agriculture, Fisheries and Food (ADAS), and to other interested people. For some species, this system is as effective in detecting the arrival of aphids as regular inspection of crops, and much less expensive. The suction traps used are very sensitive and capable of measuring airborne populations so sparse that, when deposited on the ground, they would be difficult to detect even with careful searching.

Many other insects of agricultural interest are sampled by this system of suction traps, which provides information on the seasonal movement of airborne populations over large areas.

In addition to the suction traps, an extensive system of light traps is operated, with the help of numerous volunteers many of whom are amateurs, to collect information on the density and dispersal of populations of night-flying insects. These include about 30 species of moths of agricultural interest, crane flies, whose larvae, leatherjackets, are soil pests, and beneficial predators including lacewings.

The Insect Survey serves not only an immediate practical purpose, but also provides the data essential for the study of insect population changes in relation to land use and agricultural practice. This unique information is used in other departments at Rothamsted, and at several research centres elsewhere.

An entirely different method for monitoring insect populations is the use of simple traps containing a sex attractant. This approach, developed in co-operation with the Insecticides and Fungicides Department, has the advantage of being cheap, extremely sensitive and usually specific for a single pest, so that much of the labour needed to sort and identify catches is eliminated. These traps can be sited within growing crops so that an individual farmer can use them to make his own pest assessment, or they can be used by ADAS Agricultural Advisers or commercial organisations as a basis for regional spray warnings. So far, the method has been successful for pea moth; the possibilities for other moths, and for wheat bulb fly, are being investigated.

Weather and population changes. The effect of temperature, wind and rainfall on the numbers and activity of pest populations is profound, and impinges upon almost all field pest problems.

Slug and leatherjacket populations are difficult to measure and their activity is difficult to predict. Both are related in a complex way to rising and falling temperatures, humidities and perhaps also daylight. Long-term observations on field populations of these two pests in relation to weather should provide information leading to early warning of infestations and more effective use of present molluscicides and insecticides. The long-term information collected on aphid and moth populations enables their abundance and distribution to be mapped and linked with weather.

Direct drilling. The drilling of crops directly into an uncultivated soil that has been treated with a broad-spectrum herbicide to kill existing vegetation is becoming increasingly common. This practice greatly changes the pest and disease problems, increasing some and diminishing others. Furthermore, there is evidence that soil-dwelling invertebrates that do not contribute greatly to soil fertility in ploughed soil, are much more important in unploughed soil because they provide channels and crevices for root growth.

This is especially true of earthworms, whose role in the breakdown of organic matter and its incorporation into the soil is so important.

Economic aspects of applied entomology. Once the type and size of a pest problem has been identified, it is essential to assess whether the damage is of sufficient economic importance to merit control, and if so to determine the best method to use.

Insect pests and crop yields. Knowledge of the relationship between insect pest populations and crop growth and yield is essential to pest management and the prevention of yield losses. The effects of pest attacks can differ greatly between sites and seasons, being dependent not only on pest numbers, but on the growth stage of the crop when attacked, crop variety, soil conditions, weather and many other factors. This variability often makes it difficult to define pest populations that justify control, and intensive investigations are needed to measure yield losses and discover how they are caused. Pests that are being studied in this way include some on grass, cereals, field beans and oilseed rape.

As part of an overall Rothamsted programme the department is collaborating in studies to assess the relative importance to field crop production of insect pests compared with other factors affecting the yield, such as soil fertility, weather, pathogens and nematodes.

The economics of pest damage, pest control and beneficial insects are being evaluated for some field crops to determine priorities in research and advisory work.

Pollination of field crops. Rothamsted has long held an authoritative position in this subject and work continues on assessing the economic returns obtained from using honeybees to supplement existing pollination of field crops, and on ways of increasing the efficiency of honeybee colonies used for pollination. The latter include studies on the technical and economic feasibility of using pheromones to manipulate foraging behaviour and colony management.

Side-effects and limitations of pesticides. Unfortunately many pesticides kill beneficial animals as well as the target pests, and the harmful insects themselves may develop resistance to them.

Pesticides and beneficial animals. Sometimes pesticides harm populations of carabid and staphylinid beetles, other predators and parasites, and soil arthropods and earthworms important in the breakdown of plant litter and its incorporation into the soil. Bees and other important pollinating insects are also often killed. Pest populations have sometimes even increased following insecticide treatments that destroy predators more rapidly and effectively than the pests themselves. Several experiments to monitor the effects of pesticides on populations of soil animals, especially earthworms, and the breakdown of organic matter, are in progress. A long-term experiment is maintained in Appletree Field in which the effects of various pesticides on soil invertebrates are measured. The aim is to discover which of the pesticides currently available for decreasing the population of a particular pest is least likely to damage or kill beneficial organisms. This work is becoming increasingly important as so-called 'integrated' methods of pest management are more

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widely adopted. Chemicals aimed at insects, weeds and fungi can all on occasion harm some kinds of beneficial organisms and so need their short-term and long-term effects assessed.

An investigation into ways of combining conventional pesticides and beneficial organisms to control cereal pests is in progress in collaboration with the Glasshouse Crops Research Institute and the Game Conservancy. The department also collaborates with the Insecticides and Fungicides Department to develop methods of controlling pests, such as the bean aphid (blackfly) and pests of oilseed rape, with minimum harm to the beneficial insects, especially bees, that are attracted by the flowers.

Resistance to insecticides. A potentially serious hazard to many important crops, especially potatoes and sugar beet, is the development of widespread resistance to organophosphorus insecticides currently used for aphid control. Working closely with the Insecticides and Fungicides Department it is hoped to discover whether resistance is associated with particular crops, pesticides, or spraying sequences, and eventually to explain its genetic basis so that practices that minimise its development can be adopted.

New methods of control. Because conventional insecticide treatments often produce undesirable and unexpected side-effects, new ways of controlling pest populations are always being sought, and several interesting possibilities are being examined.

Pheromones, sex attractants and inhibitors. Potent chemical messengers widely used by insects for communication, may also be exploited to control pest outbreaks. For example, the dissemination of a sex attractant or its inhibitor in a crop may so disorientate and confuse males searching for females, that few pairs meet, successful matings decrease, and a high proportion of sterile eggs are laid. Alternatively, it may be possible to attract a high proportion of males in a population to a pheromone source, and kill them there, so that too few remain in the population to fertilise all the females.

These possibilities, which would be most unlikely to provide environmental side-effects, are being studied for several pests, especially moths and flies.

Food attractants and baits for slugs. Improved or new molluscicides may result from studies on the chemicals in plants to which slugs are attracted to feed. When added to baits, extracts of wheat bran, carrot and maize enhance the prospects of the bait being found and eaten by slugs. More effective and safer ways of incorporating the toxic chemicals into slug baits are being explored.

Control by pathogens. Insect pathogens have been studied intensively at Rothamsted since the mid-1930s as the causes of many diseases of honeybees. The identity and importance of many, including several recently discovered viruses, have been established. Methods of controlling them are continuously sought and evaluated. The pathogens of other insects also are now receiving attention but with the contrary aim of spreading them as a means of pest control. For example, pathogenic fungi often kill individual aphids and wheat bulb flies but unfortunately levels of infection high enough to decrease populations substantially do not occur naturally until the pests have already

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damaged crops. The possibility of introducing spores artificially early in the season is being studied but success is likely to be dependent on weather. This method is attractive, like control by pheromones, because of its relative specificity and absence of undesirable environmental effects.

Fundamental studies. Many aspects of the work are based on fundamental scientific studies without which progress on the applied topics described above would be difficult or impossible.

Mechanisms of chemical communication. The organisation of a honeybee colony requires many different facts to be communicated between individual insects, and many of the signals they emit are probably at least partially chemical. For this reason bees are being used as convenient experimental insects with which to investigate the physical and chemical properties of pheromones and how they are used by insects for different types of communication. This work necessarily includes studies of the morphology and function of antennal receptors of bees and other insects.

Population dynamics. New ways of collating and analysing the vast amount of data collected by the department on insect abundance and movement are constantly being sought to provide a better understanding of the fundamental causes of changes in pest populations.

Taxonomy of insects and micro-organisms. Underlying the work of the whole department is the ability of many staff to identify the pests and related insects caught in traps and crops, and the micro-organisms associated with them. Experts in the systematics of aphids, flies, moths, parasitic wasps, thrips, beetles, earthworms and insect pathogens contribute to the whole effort through their studies on insect morphology, physico-chemical properties of viruses, and cultural characteristics of bacteria and fungi.

INSECTICIDES AND FUNGICIDES DEPARTMENT

The work of the chemists and biologists in the department is aimed at making chemical control of pests and diseases more efficient and safer. This includes developing and evaluating novel methods of crop protection such as the use of chemicals which modify insect behaviour. However, major dependence on conventional insecticides and fungicides, sometimes in conjunction with novel methods, will continue for the foreseeable future, so that studies on these compounds form the major part of the research programme. This involves both laboratory and field work, and ranges from the investigation of immediate practical problems to basic studies on how crop protection chemicals act and on the factors which influence performance.

Relationships between molecular structure and insecticidal activity. Most relationships between molecular structure and insecticidal activity are still poorly understood, and better knowledge is needed to provide a fully rational basis for finding new and better toxicants. In recent work the department has concentrated on compounds related to the natural insecticides found in

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pyrethrum flowers, which are outstandingly safe to mammals and have very favourable properties in the environment. Synthesis of many different compounds and examination of their chemical and biological properties has revealed many of the chemical features required for insecticidal activity. One outcome of this work has been the discovery of several outstandingly active new synthetic insecticides, some of which are in commercial production. Previous pyrethroids were employed mostly indoors and in the glasshouse because they are expensive and decompose very rapidly outdoors. Some of the most recently discovered compounds, however, are cheaper and more stable while retaining the favourable properties of previous pyrethroids, and so extend the scope of the group, particularly for controlling pests in agriculture and horticulture.

Mode of action of insecticides and the causes of resistance. As with studies on structure/activity relationships, investigation of the mechanisms involved in the poisoning process gives information needed to use existing pesticides to the best advantage and to develop better ones more rationally. Biochemical, neuroanatomical and electrophysiological methods are therefore being used to identify the critical sites of action and the biochemical systems involved and to determine the importance of the various factors that govern the amount of toxicant which reaches these sites. Insecticides from various classes are being studied, including the pyrethroids, so that information is made available to guide the synthesis of new compounds.

Resistance is one of the most important problems associated with the use of insecticides throughout the world, and is becoming progressively more serious. Fundamental toxicological, genetical and biochemical studies in the department are helping to elucidate the nature and importance of the mechanisms responsible for resistance, using houseflies, which are particularly suitable for this type of experimental work. Knowledge thus gained is now being applied to the study of resistance to insecticides in aphids in the field with the objective of developing insecticidal regimes which will prevent or delay the development of resistance.

The mode of action of fungicides and the causes of tolerance. Fungicides are used increasingly to control powdery mildews on cereals and factors determining their activity are being examined. Biochemical and physiological studies to determine mode of action form a major part of this work which has concentrated so far on the fungicide ethirimol. Strains of mildew tolerant to ethirimol have been detected in the field, and by examining the factors which influence their survival, it is hoped to devise procedures to limit the spread of such strains within the population. The problems posed by tolerance of pathogens to fungicides have much in common with those associated with resistance to insecticides and there are some similarities in method of approach.

Influence of environmental factors and formulation on the persistence, movement and effectiveness of pesticides. The effectiveness of a pesticide depends not only on its toxicity, but also on how much can reach the target organism following application in practice. At present pesticides are mostly used very inefficiently, with only a very small fraction of the amount applied reaching the intended target. The remainder enters the environment and may affect non-target organisms without contributing to pest control.

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To suggest possible improvements, it is necessary to know accurately how pesticides are distributed by different methods of application and to understand how they persist and are redistributed subsequently. Complementary information about the characteristics of target organisms as recipients for pesticides is also needed. These factors are being studied for both foliar and soil treatments. The knowledge obtained provides a basis for suggesting ways to make pesticides application more selective and efficient by better timing, distribution, or formulation. Current work includes the development of a charged droplet application method to improve thoroughness and efficiency of cover by foliar sprays.

Several important pests and diseases can be controlled by systemic chemicals which are taken up and translocated by plants following application to the foliage or to the soil. This method has many advantages and the principles involved are being examined in detail.

Control of soil-borne pests and diseases. Soil-borne pests and diseases are among the most difficult to control and in addition to the work on underlying principles described in the preceding section, practical control measures are also being studied. For example, in collaboration with the Agricultural Development and Advisory Service of the Ministry of Agriculture, Fisheries and Food (ADAS) more effective chemicals for controlling wheat bulb fly larvae (*Delia coarctata*) are being sought. Although some recent chemicals are moderately successful, no entirely satisfactory alternatives for the organochlorine insecticides have yet been found. In collaboration with the Entomology Department, methods for controlling slugs are also being investigated.

In theory seed treatment is a particularly convenient, economical and selective method for controlling seed- and soil-borne pests and diseases, as well as for applying systemic compounds. Previous work in the department showed, however, that commercial methods of applying both liquid and powder treatments were unsatisfactory and stimulated manufacturers to produce improved seed treatment machinery. In related studies the biological requirements for control are being investigated, both for soil- and seed-borne diseases controlled by fungicide seed treatments and for soil-borne pests such as wheat bulb fly larvae.

Harmful side effects of pesticides on beneficial insects. It is obviously desirable that damage by pesticides to pollinating insects and to the natural enemies of pests should be kept to a minimum. In collaboration with the Ministry of Agriculture, Fisheries and Food, samples of bees suspected of being poisoned and sent by beekeepers to the Bee Advisory Service are examined. This enables the main causes of bee poisoning in practice to be identified so that methods of avoiding harm can be suggested. The toxicity of currently used pesticides to bees is tested in the laboratory and advice is given about field trials. The possibilities of decreasing damage to pollinating insects without diminishing control of the pests by altering factors such as choice of toxicant and formulation, timing of applications and dose rates are being investigated. Similar factors are being studied for predators and parasites of aphids with the aim of allowing such natural enemies to contribute as much as possible to control so that less pesticide can be used, in keeping with the concept now known as 'integrated control'.

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Chemicals influencing pest behaviour. Insects respond to a wide variety of chemicals which influence activities such as mating, the avoidance of predators and the location of food and of sites for laying eggs. These chemicals are being studied because of their possible use for monitoring or locating pest populations, or for controlling them by disrupting normal behaviour.

For examples studies, in conjunction with the Entomology Department, on the sex pheromone of the pea moth have led to a new system for monitoring pea moth populations as an aid to chemical control. Pheromones from other insects such as aphids, bees, diamond-back moths and flour moths are also being studied. Work is in progress on chemicals influencing host plant selection by slugs and wheat bulb fly larvae, and on the influence of plant constitutents on aphid feeding.

Foliar sprays for controlling soil-borne diseases. Soil-borne diseases have traditionally been controlled by applying fungicides to the soil and previous work in the department has sought improved materials for this purpose. However, soil treatments have several disadvantages and current glasshouse and field studies are aimed at finding compounds which exert fungicidal action below ground after application to the foliage. Various chemicals capable of controlling common scab of potato and beetroot (caused by *Streptomyces scabies*) and clubroot of cabbage (caused by *Plasmodiophora brassicae*) following application to the leaves have now been discovered; their mechanisms of action are being investigated in physiological and biochemical studies and other soil-borne diseases are being studied.

The Chemical Liaison Unit

This unit, associated with the Insecticides and Fungicides Department, comprises chemists whose function is to obtain information about the application, redistribution and persistence of crop protection and other chemicals to assist the work of biologists in other departments. Its broad objectives are to improve the practical use of crop protection chemicals and to assist studies of their biological effects. Much of the work is devoted to problems of immediate practical importance and the programme depends largely on the needs of the biological departments but underlying principles are studied whenever possible. Relationships between physical and chemical properties of chemicals and their mobility in soil, uptake by plants and degradation have a common basis whatever the biological activity of the compounds involved. Some current projects are given below.

Control of nematodes. The persistence and mobility of non-fumigant nematicides in soil and their initial distribution following different methods of application are being examined in relation to their effects on crop yields and the development of potato cyst-nematodes. Residues in several crops are monitored in relation to dose and time of application.

Fungicides for controlling tuber-borne diseases of potatoes. Methods of applying fungicides to potato tubers for controlling tuber-borne diseases are being evaluated. The initial distribution of chemical after application and subsequent penetration, translocation and metabolism, both in the tuber during storage and in the growing plant are being measured and related to

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disease control. This study, like that on nematicides described above, is typical of many undertaken by the unit to relate the distribution of chemicals to their biological effects.

Moulding of hay. Various chemicals such as propionic acid are active against organisms causing moulding of hay but have proved unreliable in practice. The application, redistribution and biological effectiveness of such chemicals is therefore being studied with the objective of developing improved methods of treatment.

Nitrification inhibitors. The persistence, distribution and effectiveness of nitrification inhibitors in soil are being examined in conjunction with agronomic work by the Soils and Plant Nutrition Department.

Long-term effects of applying crop-protection chemicals. At present little is known about the long-term effects on soil of repeated treatments with combinations of crop-protection chemicals. The effects of repeated treatments with combinations of representative herbicides, insecticides and fungicides on crop yields and residue levels in soil are therefore being examined.

MOLECULAR STRUCTURES DEPARTMENT

This department was set up in April 1973. The general theme of its work is the relation of molecular structure to biological activity.

Co-ordination chemistry. The main emphasis is on the chemistry of major plant nutrients, potassium, magnesium, and calcium, and, in addition on that of sodium, rubidium, caesium, strontium and barium. We synthesise compounds which form complexes with these metals and seek those which will be selective in their action. The long-term aim is to discover how plants take up into the leaves more potassium than sodium, and why a few plants (e.g. sugar beet) require the latter element for growth. We observe the effects of these compounds on the transpiration of plants, and particularly on the openings of the stomata in the leaves. We are not yet in a position to say that we understand what is happening at the molecular level and to test the theory by experiment in the field.

Crystal structure determination. If a new chemical compound has been obtained either by extraction from a plant or animal source or by synthesis in the laboratory it is often necessary to know, not only the numbers and kinds of atoms present, but also how they are arranged with respect to one another. If the compound is crystalline this information, i.e. the molecular structure including bond lengths and angles, can be obtained by placing a single crystal in a beam of X-rays, collecting the diffraction pattern and (after much calculation) obtaining a three-dimensional picture of all the atoms in one molecule and of the way the molecules are packed together to give the complete crystal. We use this technique to solve three kinds of problem.

The first arises in co-ordination chemistry; here the interest lies in knowing what atoms are in contact with the metal, and at what distances. This informa-

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tion leads to the next stage, attempting to predict the kind of molecule that will attach preferentially to a particular metal. It is also possible to observe the difference between a molecule when attached to the metal and in its pure, uncomplexed form. This is useful in the design of potential complex-forming molecules. Only some of the conceivable changes, those requiring little energy, are found and the new molecule must be able to form complexes also with small energy requirements.

In the second class of problem the technique is used to establish the chemical constitution of a compound extracted from a natural product. Colleagues (in Rothamsted or in other laboratories of the Agricultural Research Service) who have extracted the compounds bring the problem to us if the results of other investigations are equivocal, an indication that the compound contains some novel structural feature. An example of this was the identification of phytuberin, a compound isolated from blighted potatoes by chemists in the Food Research Institute.

In the third class of problem we are collaborating with the Insecticides and Fungicides Department to determine the 'absolute configuration' of some of the powerful new insecticides they have recently developed. Many compounds produced by plants or animals, including insects, are of either a right-handed or a left-handed form. (Right and left hands are mirror images which cannot be placed in any way to make them identical). Although it is easy by optical methods to discover that the molecules have handedness, X-ray diffraction is the only method available for determining directly whether the molecule is actually right or left-handed, i. e. the absolute configuration. The site of action of a biologically-active compound can be imagined as the mould of which the compound is the casting; if the configuration of the casting is known, that of the mould can be deduced and used in the design of further biologically-active molecules.

NEMATOLOGY DEPARTMENT

The department studies nematodes (eelworms) known or suspected to be plant parasites, of which over 2000 species have been described. A few live and feed on or in the aerial parts of plants, some are internal parasites of roots but most live in the soil and feed externally on roots or underground stems. There are also many other species of nematodes in soil, some of which feed on bacteria, some on fungi and some on other nematodes. Wounds or rotting plant tissue almost always contain free-living species, whether or not they also contain plant parasites. Because they are small, about a millimetre long, work with nematodes involves much microscopy and their extraction from soil or plants is a tedious process.

Identification, structure and biology. Identification, classification and the description of new species are an important part of the department's work, and to aid this a reference collection of specimens has been built up over the last 30 years. Special attention is paid to economically important genera of cyst-nematodes (*Heterodera* and *Globodera* spp.), to root-lesion nematodes (*Pratylenchus* spp.), spiral nematodes (*Helicotylenchus* and *Rotylenchus* spp.), the vectors of soil-borne viruses (*Xiphinema*, *Longidorus*, *Trichodorus* and

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Paratrichodorus) and root-knot nematodes (*Meloidogyne*), which are of major importance in the tropics. Their identification calls for knowledge of their detailed structure, which requires refined microscopic techniques. The scanning and transmission electron microscopes are used to study details of morphology beyond the resolving power of light microscopes. The functions of organs are investigated using advanced photographic methods including cinemicrographic analysis. The life cycles and host ranges, both crops and weeds, are determined, for this knowledge is essential for controlling pests by suitable crop rotations.

Stem nematodes. Races of *Ditylenchus dipsaci* attack a wide range of plants and their pathogenicity, biology and taxonomic status is studied to provide a backgound for work on their control. Farm experiments include the effect of the races on plant growth and grain yield and also the survival of the nematode in the soil which may exceed 5 years without a host crop. Methods of disinfesting seed are being sought.

Ectoparasitic nematodes of roots. In sandy soils, many crops are stunted by the feeding of ectoparasitic nematodes belonging to the genera *Trichodorus* and *Paratrichodorus* (stubby root nematodes) and *Longidorus* (needle nematodes). Although both genera often transmit viruses, the damage caused directly by the nematodes is often greater than that of the viruses they transmit. Several genera of root ectoparasitic nematodes are implicated in crop damage either alone or in association with each other or with other pathogens. Further information on the biology and damaging effects of root ectoparasitic nematodes is being sought.

Root lesion nematodes. Root lesion nematodes *Pratylenchus* spp., are the commonest and most numerous migratory nematodes associated with cereals. In some parts of the country, especially on lighter soils, and where cereals are grown often, they probably cause damage. Five species found in cereal fields are cultured in the laboratory for studies of pathogenicity and interactions with other pathogens. Field experiments are being done to seek ways of controlling *Pratylenchus* on field beans.

Cyst nematodes. Of the important cyst nematodes, that of cereals (*Heterodera avenae*) is widespread at both farms, the beet cyst-nematode (*H. schachtii*) occurs at Rothamsted and the potato cyst-nematode (*Globodera rostochiensis*) on old allotments at Rothamsted and on most fields at Woburn. Possibly because the Rothamsted soil is clayey and close-textured, cyst nematodes cause much less trouble than on the lighter soils at Woburn, where cereals and potatoes are harmed when grown in crop rotations that would be safe at Rothamsted. Two species attack potatoes in the United Kingdom and each exists as a series of races or pathotypes. The department collaborates with the Agricultural Development and Advisory Service (ADAS) and with nematologists overseas in typing populations and standardising nomenclature. Many British and foreign populations are maintained under licence and staff members have visited the USA, Mexico, Venezuela, Peru and Bolivia to study populations there. The genetics of inter-relationships of pathotypes and hosts are studied. This work is valuable for plant breeders and essential if rational use is to be made of the nematode-resistant varieties they produce. Recently,

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naturally occurring fungi have been shown to depress field populations of *H. avenae* and they may also affect *H. schachtii* and others. Such fungi may have a potential as biological control agents.

Other work on cyst nematodes includes studies of behaviour, mating and sex determination, as well as detailed studies of morphology using the scanning and transmission electron microscopes.

Control by nematicides. The department does many experiments every year on the Rothamsted and Woburn farms and elsewhere with field and glasshouse crops to study control by nematicides. Severe damage to onions by stem nematode (*Ditylenchus dipsaci*) can be minimised by applying small amounts of oximecarbamate or organophosphate nematicides in the seed furrows at sowing time but a treatment has yet to be found which can prevent a rapid increase of the nematode in the crop late in the season. Cyst nematodes, especially potato cyst-nematodes, have been controlled by incorporating organophosphate or oximecarbamate nematicides in the seedbed. The best of these treatments not only prevent damage to the crop but also lessen or prevent nematode increase. The effectiveness of a nematicide is much affected by the way in which it is applied and a new method of application which causes minimum damage to soil structure has been patented (see Plate opposite p. 24). To ensure safe as well as effective use of nematicides, their persistence, movement and decomposition in soils and crops is investigated.

Tropical nematodes. The department houses the Overseas Development Administration Nematology Liaison Officer who works on a variety of problems caused by plant nematodes in the tropics and sub-tropics.

PHYSICS DEPARTMENT

Plants grow partly in the soil and partly in the air, and the growth of one part is affected by the growth of the other, with each of them dependent on physical, chemical and biological factors in their environment. These factors interact, and much of the work of the Station goes into attempts to sort out the nature of the interactions, and the effect they have on crop yields. The department's field experiments attempt to stabilise (or eliminate) factors other than physical: the requirement is for healthy plants growing on well managed soil and sustained by the best possible crop husbandry. We then seek to control and measure the physical variables in so far as we are able. For example, the mobile shelters (at the Little Knott site) are designed to move automatically to cover a field-growing crop during rain periods. They constitute an important facility that allows the crop's water requirement to be supplied, by irrigation, or withheld, while the crop's exposure to the other weather elements is similar to that of the open field.

Soil problems

Cultivation. What is 'Well managed soil'? The problems of minimum tillage, plus those arising from the passage of very heavy modern farm equipment over the soil and from the high costs of tractor fuel, justify a fresh look at what cultivation does to the soil, and in the context of the physical environment the interest is in effects on soil temperature and heat flow, soil

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water, soil aeration and on mechanical impedance to root growth. Incorporated within the mobile shelter facility is a series of concrete tracks that allows cultivation of the soil while keeping the tractive effort clear of the soil, thus the desired experimental variables can be imposed without unwanted effects of tractor compression.

Soil structure. Structure is a description of the soil matrix upon which a growing plant depends; it is characterised in terms of the types, shapes and sizes of constituent particles both at the micro- and macroscopic levels, and in terms of the mechanisms which cause them to be arranged into crumbs and peds. Because such an environment is often transient, due to the effects of weather and cultivation, soil structural stability is also an important factor in determining crop yield. The basis for research activity lies therefore in measuring stability and interpreting the results in terms of fundamental physical processes as well as relating them to other soil parameters.

Soil water. Fundamental work on the retention and movement of soil water has applications to land-drainage, irrigation, soil-water profile development and soil classification, soil mechanics, and the role of the soil as the environment of plant roots. The research is concerned with the development of theory and its application to practical soil-water problems. Currently, aspects of soil heterogeneity, soil swelling and hysteretic effects in soil-water relationships are being studied, and contributions made to land-drainage theory.

Soil atmosphere. The part of the pore-space not occupied by water is gas-filled, and usually contains much more carbon dioxide than there is in the free atmosphere. Biological activity in the soil needs a renewal of oxygen and expulsion of carbon dioxide. Gases diffuse into most soils fast enough to meet the requirement for gas exchange, at least as far as the outside of the soil crumbs; the critical control of aeration is within the crumbs, and laboratory work is concentrated on the effect of crumb structure—and its complex geometry—on gas movement to and from respiring organisms.

Agricultural meteorology. Oversimplifying, there are two groups of problems in agricultural meteorology. In the first group are those of weather physics, which would demand study whatever the nature of the surface of the boundary between solid earth and the air above it. In the second group are the problems associated with the nature of the surface, separable into two sub-groups of, first, the effect of the crop on the weather physics, and second, the effect of weather on the plants. The field part of this latter work is supplemented by laboratory research in plant physiology directed toward *physical* interpretation of what happens in the field.

Soil-water use (field). Great Field—a large field, and until recently uniformly-fertilised—was used for several years for studies of irrigation, evaporation and crop water use. However, responses to irrigation of many crops can be produced on Great Field (as in most of southern England) *only* in summers somewhat drier than average. Much of this work is therefore now carried out in Little Knott, where mobile rain shelters permit drought extremes to be imposed as desired, and where in experiments in 1976 and 1979 barley crops were subjected to different degrees of drought at different stages of growth (see Plant and Crop Physics section, below).

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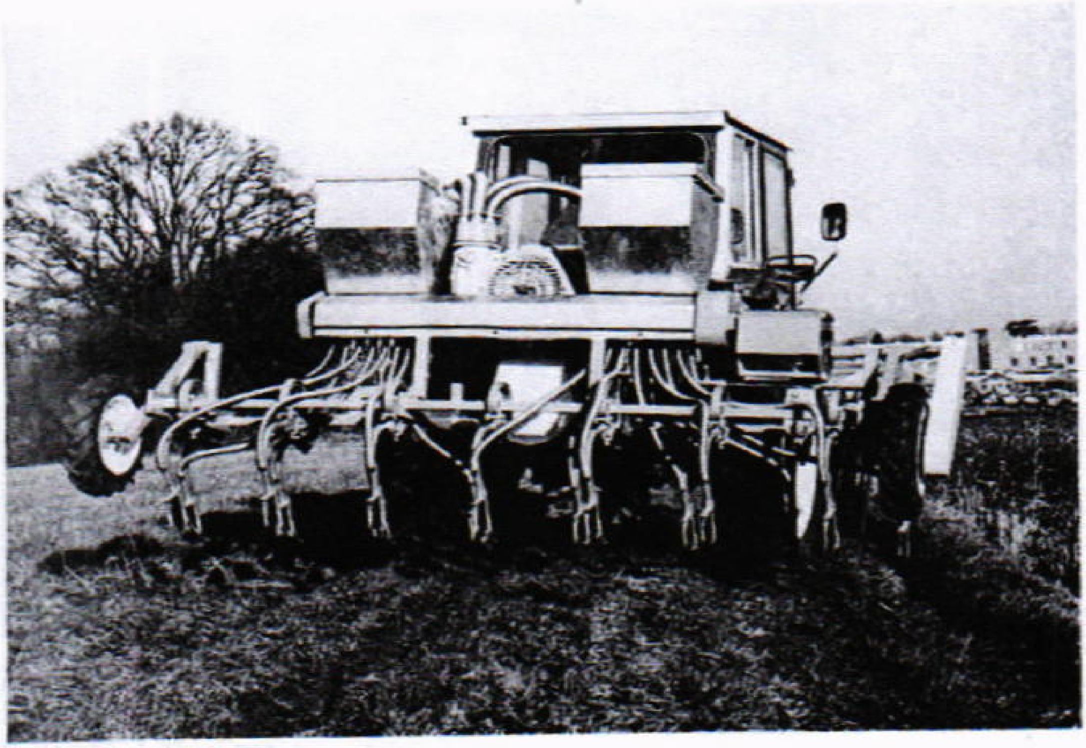
(a)

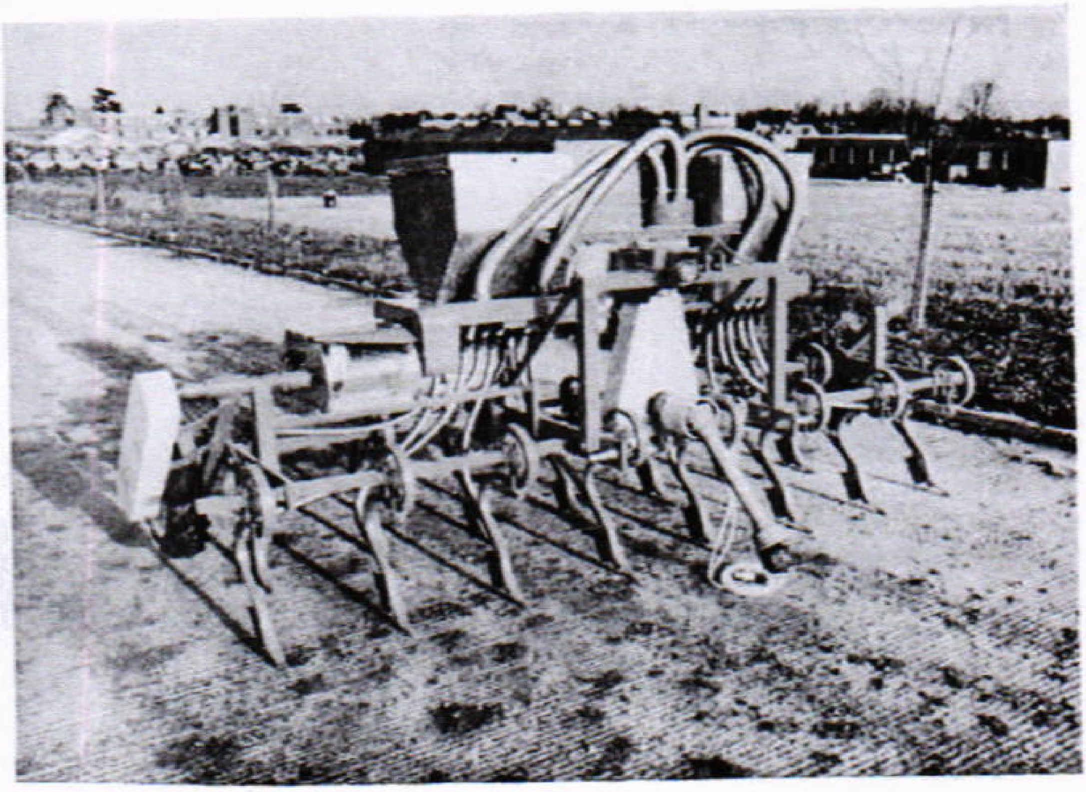
(b)

(c)

Rothamsted Laboratories: (a) Testimonial Laboratory, 1855; (b) Russell Building, 1913–14; (c) Daniel Hall Building, 1977



Rothamsted 'Vertical Band' granule applicator. This machine, followed by a rotary harrow, enables nematicide granules to be mixed safely and efficiently with the top 10-15 cm of the soil without harming soil structure



B*

Experiments excluding surface-living predators of cereal aphids

Stereoscan photograph of soil-inhabiting mite (family Oribatidae) important in maintaining soil fertility

Sorting insects used in the testing of synthetic pyrethroids

Studying the leaching and degradation of pesticides in the soil under field conditions

Nonetheless, part of Great Field is still used for water relations studies, as part of the series of deep cultivation and fertiliser placement experiments (see p. 68); measurements are made of the water potentials of the plants and the soil as they are affected by subsoil cultivations and by the application at depth of phosphorus and potassium fertilisers.

Aerobiology. In the eastern part of Great Field, alongside the meteorological enclosure, experiments are now directed to studies of the movement and deposition of cereal disease spores (with Plant Pathology Department). These movements are very much influenced by the strength and turbulence of the wind, and appropriate sensors are deployed within and above the studied crop to measure these wind components, which are then recorded on a dedicated computer. Rates of deposition are measured for liquid particles (simulating mildew spores) that are released from a spray drop generator that traverses a railed track alongside the crop. A wind tunnel is used in supporting studies, and the research objective is to develop a mathematical description of the spread of disease spores that will aid strategies of disease control.

Plant and crop physics. We investigate physical aspects of plant physiology—including the gas exchange processes of photosynthesis and transpiration—which we seek to describe by physical models.

In the field, measurements are made of plant growth and of crop physical structure. The gas exchanges of individual leaves are measured using a small leaf chamber and porometer; leaf growth is measured continuously with auxanometers. Above and within the plant canopy, supporting measurements are made of various physical variables, including light intensity, humidity, and air and plant temperatures. In addition, the water potentials of various plant parts are determined, as are the responses of photosynthesis rates to changes in light intensity and carbon dioxide concentration.

Physical parameters that describe the functioning both of leaves and of whole crops may be derived from these various measurements. If the physical variables are then measured in the field, then the parameters and variables can be combined in models that predict the expected growth of these field plants. The suitability of the models is assessed through a comparison of their predictions with the growth actually measured.

This approach is applied in the Little Knott studies of the drought response of crops, where rainfall is eliminated by the shelters, and controlled irrigation gives treatments ranging from no applied water (so the crop grows on stored water alone) to regular weekly irrigation. Studies are made of plant response and aerial environment, and also of soil-water properties so that the drought treatments can be quantified and so that effects on the depths and amounts of water abstraction can be determined.

Instrumentation. Many of the measurements that we require to make are so specialised that no suitable measuring apparatus is commercially available. Much effort is therefore devoted to the development of sensors to measure such variables as soil, air and leaf temperature, air humidity, soil heat flux and thermal conductivity, soil moisture content, horizontal wind speed within a crop and the vertical wind speed of turbulent eddies.

Routine meteorology. The Physics Department is responsible for collecting and reporting the weather records from the meteorological enclosure at

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Rothamsted (see p. 45), and for reporting records from Woburn. A detailed survey of the Rothamsted records is in Part 2 of the *Rothamsted Report for 1973*, and a summary of the records from both Rothamsted and Woburn is given in Part 2 of the *Rothamsted Report for 1979*.

PLANT PATHOLOGY DEPARTMENT

Every year plant diseases cause significant losses to growing and stored crops, losses which would be much greater if various control measures were not used. The task of this department is to identify the causes of disease, to determine the effects on the host plant and to elucidate the factors involved in the development of disease epidemics with the objective of improving control methods. Of a staff of about 50, one quarter study viruses and virus diseases, one half study diseases caused by fungi, bacteria and other pathogens and the remainder provide services such as glasshouse facilities and electron microscopy and secretarial support. Most work is on cereals and potatoes but attention is also given to other crops of current or potential agricultural importance such as grasses, forage and grain legumes, oilseed rape and maize. The department maintains a large programme of field experiments at Rothamsted and elsewhere, supported by work in the laboratories, glasshouses and controlled environment rooms.

Viruses. These are very small pathogens that multiply only in living cells. The particles have two major components; nucleic acid, the infective part and protein, which protects and stabilises it. To study their shape, size and distribution in infected cells, extracts of purified preparations or ultra-thin sections of infected tissue are examined under the very high magnification (40 000 ×) of the electron microscope. The particles are penetrated so easily by the electron beam that they must be immersed in stains that absorb electrons to make them visible. In addition to studying their morphology, viruses are identified by the symptoms they cause in natural hosts and when transmitted to selected indicator plants; by serological tests that utilise antibodies specific to the virus protein that are formed in the blood serum of rabbits injected with the virus; and by the means by which they are transmitted from one host to another. Most viruses can be transmitted by grafting, many by mechanical means that involve wounding and some only by vectors such as insects, mites, nematodes and soil fungi. Some viruses are transmitted in the seed from infected plants and, in vegetatively propagated crops, perpetuation in the planting material is important.

Effects of viruses. Potato yields are severely decreased by virus infection and virus-free seed tubers have to be obtained to maintain yields of crops grown in southern and eastern England. Field beans (*Vicia faba*) a valuable source of protein would be grown more widely if yields were more reliable. Virus diseases, weather and attacks by insects, nematodes and fungi have been shown to be important causes of this unreliability. Several bean viruses are transmitted by aphids but two, broad bean stain virus and broad bean true mosaic are seed-borne and transmitted by weevils. Measuring the effect of viruses is difficult because severe and mild isolates often exist and their

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relative prevalence differs from area to area and season to season. Plants are often affected differently according to the age or growth stage at which infection occurs. For example, early infection of cereals with barley yellow dwarf virus is very damaging, the less so the later the infection. Some crop plants, notably ryegrass, sugar beet, *Vicia* beans and clovers and also the mycelium of many fungi including plant pathogens, contain virus-like particles with which we have been unable to associate symptoms or harm.

Control of virus disease. Plant viruses are so intimately involved with cell metabolism that it is seldom possible to inhibit their multiplication without damaging the host plants. Control is based on planting healthy crops and then preventing the spread of viruses into them. Healthy plants can be regenerated from infected stocks by 'heat therapy' whereby infected plants are kept at 35°C until they become virus-free, or by 'apical meristem' culture in which minute fragments of apical buds are freed from virus during growth in tissue culture. All certified seed tubers of King Edward potatoes are derived from tissue cultures freed from paracrinkle virus in this laboratory and yield 10% more than infected ones. Protection from re-infection is achieved by a combination of multiplication stock isolation, a requirement of most Certification Schemes, and the use of insecticides. Other methods to control virus diseases are being sought. Glandular hairs on the wild potato *Solanum berthaultii* trap insects and restrict their movement and feeding, so that it may be possible to control the spread of potato virus Y if glandular hairs can be introduced into commercial cultivars. Insect vectors can be controlled with pesticides. However, knowledge of how insects transmit, how long they must feed on an infected plant before they become infective and how long they remain infective is required in order to determine whether insecticides can be used effectively and economically to control virus diseases in crops.

Aphids are still the most important vectors of virus diseases in this country although improved methods of predicting and preventing their activity have provided the basis for control in potato, cereal and sugar beet crops. Viruses infecting grasses are more difficult to control because their hosts are exposed longer and reservoirs of infection are widespread. We are studying viruses transmitted by other vectors including ryegrass mosaic virus transmitted by mites and three viruses, barley yellow mosaic, oat golden stripe, and red clover necrotic mosaic, that are apparently transmitted by soil fungi.

Recent research in the field of virus inhibition has led to the discovery of synthetic chemicals able to restrict virus spread within host plants, apparently simulating the effects of some naturally-occurring inhibitors. These developments may eventually open the way to controlling viruses directly.

Mycoplasma diseases. Some diseases previously thought to be caused by viruses are now known to be associated with mycoplasmas, which are wall-less bacteria-like organisms. The range of crops affected extends from temperate to tropical climates and includes vegetable, cereal, forest and plantation crops. Evidence for mycoplasmal etiology at present depends upon electron-microscopy and chemotherapy with certain antibiotics. Work on the etiology of tropical crop diseases is often hampered by limited facilities available abroad and the department receives support from the Overseas Development Administration to help with the recognition and identification of virus and mycoplasma diseases of tropical crops.

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Fungus and other diseases. The principles underlying research on these diseases are similar to those discussed for virus diseases but the methods differ greatly and research has developed with more emphasis on crops. Some pathogens attack foliage and others roots although root disease often produces symptoms on foliage such as yellowing, wilting, retarded growth and premature senescence. Both types of disease are affected by environment and by interactions with other microbes and with soil conditions, crop nutrition and so forth. Their effects therefore have to be studied in many seasons and in the context of different crop husbandry systems. Experiments under controlled conditions in a large wind tunnel linked to a rain tower are providing more precise information about dispersal and deposition processes of air-borne and splash-borne spores, such as those of *Pseudocercosporella herpotrichoides*, the eyespot fungus. Information of this sort helps understanding of disease development in field crops and will provide the basis of improved control by chemicals or cultural practices or both. In field experiments with barley mildew, interference by transfer of disease spores from neighbouring unsprayed plots has affected disease incidence, yield and response to timed sprays and so complicated the interpretation of experiments intended to develop a sound basis for advice on control. The Statistics Department has helped us to develop experimental designs to minimise this problem or to measure the effects so that they can be taken into account in interpreting results. Some of these designs may be valuable for the study of some air-dispersed pests and virus vectors as well as for fungus pathogens.

The study of root diseases presents special problems because of the complex and variable nature of soil and its biology and the fact that the detailed examination of root systems usually entails destruction of the plants. Root diseases, unlike foliar diseases are very dependent on cropping sequences and increase where the same or similar crops are grown frequently on the same land. Some diseases such as club root of brassica crops (*Plasmodiophora brassicae*) persist for many years once the ground has become infested whereas others like take-all of cereals (*Gaeumannomyces graminis*) decline to a harmless level after a break in a cereal sequence of only 1 or 2 years. We are at present investigating whether root disease is as serious a problem where different legume species are intensively grown as it is where the same legume crop is grown frequently.

Soil-borne diseases of cereals. Consecutive cereal crops are attractive to many farmers because they are inexpensive of cultivations and labour but yields are usually less than those achieved in rotation with other crops. Foot and root rots can be very damaging and in the case of take-all (*Gaeumannomyces graminis*) no fungicides are effective and no effective sources of resistance have been discovered. Control imposes a serious constraint on cropping options, forcing some farmers to grow non-cereal crops when cereals would be preferred. Benefits from 'breaking' a sequence of cereals susceptible to take-all are only temporary because severe damage may recur in the second or third subsequent crop. However, with longer sequences of wheat or barley take-all declines to an intermediate severity, which may allow profitable continuous wheat or barley growing on some soils. The mechanisms of take-all decline are being sought, so far without success. The build up of take-all may be slower on wheat after grass leys than after other crops and this has been associated with the presence of the fungus *Phialophora* on the roots of

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ley grasses. This fungus is an avirulent pathogen on wheat roots but has been shown to restrict the development of take-all under laboratory conditions. Experiments have continued for several years to exploit this method of biological control. Changes in agricultural methods affect the importance of different diseases, some increasing and others decreasing. Reduced cultivation has increased the importance of trash-borne pathogens such as eyespot (*Pseudocercosporella herpotrichoides*) barley leaf scald (*Rhynchosporium secalis*) and the Septoria diseases. Following increases in winter barley growing, net blotch (*Helminthosporium teres*) has become more important and is now included in our studies.

Potato diseases. With the decreased incidence of potato viruses and the expansion of mechanical handling of the potato crop, fungal and bacterial diseases attacking the tubers especially through wounds, have become relatively more important. Some can be soil-borne and recent research has shown that in some cases, air-borne inoculum may be an important source of re-infection of healthier, nuclear stocks in the earliest stages of multiplication. However, in the later stages of multiplication and in the production of ware crops, the most important source of inoculum is the seed tuber. The effects of these diseases are several: they may prevent or delay emergence, decrease yield, alter tuber-size distribution, rot tubers in store, or cause unsightly blemishes, which is a continuing problem in marketing ware potatoes ready washed in transparent packs. The production of nuclear stocks is now generally based on the technique of rooting stem cuttings that we devised. However, surveys have shown that stocks so derived rapidly become as heavily contaminated and infected as any others unless they are protected during the multiplication stages by fungicides. Control by fungicides, pioneered in the department, is now widely practised to protect the ware crop in store. Work is continuing in an effort to improve the effectiveness of fungicides not only for the ware crop but with the objective of improving the ware crop through disease control in seed crops, which is much to be preferred. Meanwhile attempts to predict how well crops will store or at least to identify those unlikely to store well, by examining samples taken before lifting, will continue.

Moulding of stored grain and hay. This work developed from our spore trapping methods which were adopted by others for making 'pollen counts' to advise hay fever sufferers. This led to the recognition of many air-borne fungus spores some of which cause asthma. 'Farmer's lung' was shown to be caused by an allergic reaction in the alveoli to inhaled spores of thermophilic actinomycetes and other diseases in man and in farm animals have been shown to have similar causes. The work now includes mycotoxins and studies of the ecology of fungi able to produce these substances in cereal grains and other produce during storage. The requirements for the prevention of moulding of hay by applying preservatives such as propionic acid and its salts have been defined and the search for alternative preservatives or additives continues. The possibility of controlling fungi contaminating grain by spraying the growing crop with fungicides is being investigated, together with the effects of diseases of the growing crop and their control, on moulding of the grain in store.

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Collaboration with other departments and institutes. Much of our work requires specialist help from other departments, for example, on the nutrition of cereal and potato crops relative to diseases and on the chemistry of insecticides and fungicides and their modes of action. We in turn give advice to experimenters in other departments on how to avoid or control diseases that might complicate their results, or help them to measure possible pathological consequences of their treatments.

Increasing use is being made of the multidisciplinary approach to research in which specialists in different disciplines combine to form teams to investigate factors and their interactions that limit yields of important crops.

Our transmission and scanning electron microscopes and Quantimet 720D Image Analysing Computer and operating staff provide a service which is extensively used by other departments at Rothamsted, by other institutes and for work sponsored by the Overseas Development Administration on virus and other diseases of tropical crops.

SOIL MICROBIOLOGY DEPARTMENT

Soil contains very many different kinds of micro-organisms (bacteria, viruses, actinomycetes, fungi, protozoa and algae). In numbers of individuals they constitute the majority of living organisms and, by weight, make up a significant part of the earth's biomass. Their agricultural importance lies in their ability to break down and transform the organic and inorganic materials of the soil, so making nutrients available to crop plants. They also have many other activities, some beneficial as in promoting good soil structure and fixing nitrogen from the air and others harmful, as those causing disease. The work of the department is mainly with micro-organisms which interact directly with plants.

Micro-organisms of the plant root region. Micro-organisms in soil, especially those close to roots, affect plant growth in many ways. The effects under study are changes in the forms of nutrients available to plants, production of substances such as growth regulators and vitamins that can be taken up by plants, interactions with pathogens leading to stimulation or decrease of disease and interactions with non-pathogenic organisms that may stimulate plant growth.

Work on *Gaeumannomyces graminis* (the 'take-all' disease fungus of wheat) continues in collaboration with Plant Pathology Department.

Mycorrhiza. Mycorrhizas are non-pathogenic fungal infections of plant roots. Those studied are of the vesicular-arbuscular type, widespread in many annual and perennial crop plants. Such infections are caused by species of *Endogone* and we are studying the life histories, taxonomy and fine structure of these fungi, as well as the effects of soil type, and fertiliser and pesticide treatments and of seasonal factors on their distribution. The extent of mycorrhizal infection is being examined in a range of agricultural soils and in soils under natural vegetation in the UK and abroad. Its influence on other soil microbes, including those fixing nitrogen either in root nodules or in the rhizosphere, is receiving attention.

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In soils containing little available phosphorus mycorrhizal infection often increases phosphate uptake and thereby improves plant growth. The extent of such improvement varies with soil type and may vary with fungal species. Uptake of other nutrients and of water may also be affected. We are studying the mechanism of phosphate uptake in different soils, by mycorrhizal plants, and the effects of light, temperature and pesticides on the fungus/host relationship.

Mycorrhizal *Endogone* spp. cannot as yet be grown as saprophytes in pure culture but in working towards this objective studies are being made of the factors that control infection and fungal growth in aseptic conditions with host and fungus grown together in agar media.

Root nodule bacteria of legumes. Leguminous plants through the activity of their symbiotic bacteria can use the inexhaustible reserves of atmospheric nitrogen for their growth. This reduces the demands of these plants on soil reserves of nitrogen and often the amount of nitrogen that needs to be added to the following crop for optimal yields.

Seeds of legumes (mainly lucerne in Britain) are sometimes inoculated with nodule bacteria before sowing; this can greatly increase growth in land lacking the bacteria. However, inoculation does not always succeed, and the factors that affect this are being studied. The department maintains a collection of strains of nodule bacteria and these are being tested against various plants, to see which form the most efficient association.

SOIL SURVEY OF ENGLAND AND WALES

Land is our most important and most enduring natural resource and soil is a vital component of land. The nation needs to use and conserve its soils to maximise agricultural and forestry production and to optimise plans for protecting and improving urban and natural environments. To implement these broad requirements reliable information is needed on the quantity and quality of our land resources. The Soil Survey of England and Wales is the main source of intelligence on soil resources. Its ability to fulfil this role stems from its scientific approach, and 40 years of experience in identifying and mapping soils. In cooperation with ADAS and other ARC institutes knowledge of the practical significance of soil types is assembled to increase the precision of advice to farmers on fertiliser use, drainage, cultivation systems, irrigation and like practices as an aid to increased production. Maps and descriptive texts, that are the products of surveying, are potentially equally relevant for other uses of land since properties used to identify soil classes reflect many environmental conditions affecting local government planning, forestry, hydrology, nature conservation, recreation and civil engineering.

Survey methods. Field mapping is carried out by hand augering or digging to about 1m, to expose a column of soil—the soil profile. Its characteristics measured or observed are used to identify soil classes, that are in turn used to label areas on maps. Mineralogical, physical and chemical laboratory support is provided on a soil profile basis; there are specialist air-photo interpreters, a cartographic section and mobile drilling equipment.

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Frequency of augering depends on the scale selected for map presentation. Detailed surveys imply intensive sampling and presentation at large scale, whilst reconnaissance surveys involve low sampling density and presentation at small scale.

There have been two series of detailed surveys, published or completed at 1:63 360 and 1:25 000 respectively each of which covers about 10% of the land surface of England and Wales. Additional surveys at a variety of scales cover a further 20%, and there is a national soil map at 1:1 000 000.

In 1979 detailed surveys temporarily ceased in order to complete a National Soil Map for publication at 1:250 000; fieldwork for this project will finish in April 1982. This map will form the main physical basis for a national agricultural land classification map at the same scale.

Collaboration and consultancies. Contact with ADAS and ARC institutes is an important and very varied aspect of the Survey's work. Consultations involve provision of information from existing maps and purposive site investigations. The wide-ranging nature of cooperation is illustrated by mutual involvement in the following topics: land reclamation, site characterisations for experiments and experimental husbandry and horticultural farms, hill farm projects, design and feasibility of land drainage, assessment of minor element deficiency and toxicity, infiltration of farm wastes, within-farm allocation of land for nature conservation, land classification, site characterisation for direct drilling.

Collaboration with non-agricultural organisations that interface with agriculture, or require soil information for problem solving adds to the range of consultancies which the Survey undertakes.

Publications. Two series of coloured maps are produced at 1:63 360 and 1:25 000, the former to accompany *Memoirs* and the latter *Soil Survey Records*. These books give detailed descriptions and analyses of the soils preceded by sections on the physical environment and followed by chapters on such topics as land use capability and drainage.

A series of *County Bulletins* have also been published each accompanied by a map at 1:250 000.

In addition *Special Surveys* describe projects carried out at non-standard scales and *Technical Monographs* deal with aspects of supporting research such as mineralogy, land use capability and soil classification.

SOILS AND PLANT NUTRITION DEPARTMENT

Introduction. This department was formed in 1977 by the amalgamation of the Chemistry Department and the Pedology Department, because of their parallel interests and overlapping area of research. The Chemistry Department grew out of the original work of Lawes and Gilbert at Rothamsted, and the Pedology Department was formed in 1945 with Dr A. Muir as its first Head.

Soil is important both as the normal medium for plant growth, and as a material of great scientific interest. This department investigates the natural processes which occur in soils during their development; many of these

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processes are also of direct contemporary interest for the growth of plants. We also investigate ways of modifying soils to improve crop growth, and we are especially interested in all methods of improving crop nutrition. The production of chemical fertilisers is a major industry, and we investigate methods of utilising fertilisers more efficiently to give the most economic returns. Organic sources of plant nutrients are studied, in relation to waste disposal problems and because nutrients are released from them more slowly than from inorganic fertilisers. The interaction of plant and soil is extremely complicated, and many other disciplines are involved in the study of it. Our work therefore links closely with that of other departments studying biological and physical problems in this area.

Clay mineralogy. Clay is the most important inorganic soil constituent, because of its colloidal nature and consequent large surface area, and soil-water and soil-nutrient relationships are largely determined by the surface properties of the soil colloids. The surface properties of clays are ultimately determined by their structures, and much of our work is devoted to studying clay structures.

Soil clays are often too poorly crystalline to be amenable to detailed structure determination, but many give an X-ray powder diffraction pattern similar to a layer silicate mineral with a known structure. These clays are complex mixtures, but special treatments allow the constituent minerals to be identified. In some clays expanding and non-expanding layers are stacked together in a random or in an ordered fashion. These minerals have been difficult to distinguish from each other in the past, but are now being identified and classified using computer techniques to simulate their complex diffraction patterns.

Soil organic matter. The amount of organic matter in a soil depends on the history of the soil, its management, the soil and clay type and the climate. A change in soil management will ultimately alter the organic content of the soil and thus alter the size of the nitrogen, phosphorus and sulphur reserves; structure, structural stability, water holding capacity and exchange capacity will also be affected. We are studying some of the factors governing the amount of organic matter in soil, one of our major interests in this work being the relative stability of different fractions of the soil organic matter. From this work we hope to be able to predict the long-term effects of a given system of management on the amount of organic matter in different soils.

Another interest is the accelerated rate of mineralisation of organic matter that occurs after soils are sterilised because this casts light on the biological activity of the soil and the size of the biomass.

Organic manures have traditionally been used on crops and there is currently a movement in favour of 'organic farming'. Much work has been done on the comparison of organic and inorganic manures; usually these are equally good when compared in appropriate ways. Organic manures used regularly increase the organic matter content of soil, and this may benefit soil structure and water holding capacity. Long-term field experiments with organic manures are therefore maintained. Soil organic matter can also be increased by grass or grass/clover leys, and the department is now involved with a joint ARC/ADAS project on this topic, in addition to long-term experiments initiated earlier.

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Soil structure. Good physical structure is essential for reliable cropping. Structure depends upon the properties and quantities of both clay and organic matter in the soil, and our studies on these components aid the work on soil structure.

The formation and stability of pores in clay soils is vital to their behaviour, and we use critical point drying and mercury porosimetry to measure pore size distribution in clays. The relationship of clay type to structural behaviour is also being investigated, particularly for the interstratified materials commonly found in soil. This fundamental work is being applied in other studies on the field behaviour of clay soils, and the reasons for their different rates of regain of structure after it has been damaged are being investigated.

Soil potassium. The non-expanding layers in clay contain strongly bound potassium, and such clays, with feldspars and micas, are the main potassium bearing minerals in soil. The release rate of this potassium determines the long-term potassium supply to crops and hence fertiliser need. The factors controlling release appear to be the composition and atomic structure of the mineral, and the particle size, which together determine the ease with which potassium can diffuse out from between the layers. Models of release processes allow us to predict the amount of potassium becoming available to crops over a growing season, and we are also interested in whether plant roots have any direct action on such release rates. We are now testing the ability of our methods to predict release rates of potassium to different crops on different soils.

The long-term residual effect of potassium fertiliser is important, and one process which determines this is 'fixation', which is the reverse of the potassium release discussed above. The value of fresh and residual potassium fertiliser is being compared on field experiments, and residues are sometimes the more effective. The reasons for this are being investigated. Such studies of the long-term potassium economy of soils will allow the most efficient fertilising programmes to be designed.

Soil phosphate. Similar work to the above is also being undertaken with phosphate (the only major fertiliser element for which there is no indigenous supply). Soil binds phosphate very strongly, and most British soils now contain large reserves of added fertiliser phosphate plus the natural supply. Our field and laboratory experiments aim to utilise these phosphate reserves, and save new fertilisers as far as possible.

We are also strongly interested in biological processes which affect phosphate availability. These include the amount and rate of turnover of phosphorus in the soil biomass, which affects the availability of soil organic phosphorus. We also study the mycorrhizal fungi of roots, because they can allow plants to absorb phosphorus much more rapidly from phosphorus-deficient soils; the aim is to determine whether they have any important effect on major farm crops in Britain.

Nitrogen. Nitrogen is vital to crop yields, and is the fertiliser element most difficult to use with precision and economy because of its complicated chemical and biological reactions in the soil. The very large sum spent annually on nitrogen fertiliser, its frequently low efficiency of use, and the numerous different chemical forms and technical methods of application justify a large effort on this element.

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A major study of the nitrogen balance under wheat and grass is now in progress using ^{15}N-labelled fertiliser. This will quantify the inputs and losses of the system, and will allow us to understand the fate of fertiliser nitrogen. A major mechanism of loss is by leaching of nitrate, and this process is being followed in several fields with contrasting soils, crops and fertiliser regimes. Theoretical models to predict the amount of nutrient leaching and drainage are being tested in relation to this work. The important point is to ensure a continuous and sufficient concentration of nitrate ion in the rooting zone of the crops during their period of rapid growth, and in some trials the root-zone nitrate is monitored regularly to determine whether crop growth could be limited at any point by its low concentration. We are attempting to use such methods to predict the amount of nitrogen fertiliser needed on individual fields.

We are investigating methods of controlling the rate of nitrification of added ammonium or urea fertiliser in the soil by various chemical additives for several crops. This involves both field experiments and laboratory work on the reactions of ammonia with soil. Accurate control of nitrification could allow the ammonia to be applied in the autumn and held in the soil in this form, with subsequent nitrification in the spring and summer at the rate best matching the growth of the crop.

Nitrogen in soil is intimately associated with the organic matter, and the work on organic matter also contributes to our understanding of nitrogen behaviour.

Soil acidity. The maintenance of correct pH or acidity is of fundamental importance for crops. Acidity is associated with the appearance of aluminium ions in the soil solution, and the behaviour of these in solution and on soil surfaces is being studied. The side effects of acidity on the availability of other elements are being studied on our long-term liming experiments.

Trace elements. The trace elements have an extremely complex soil chemistry. The availability of a given trace element to plants is only slightly related to its total concentration in the soil, and the various forms in which the trace metals are present are being studied. The processes which bring metals into solution are of special interest, since these determine how readily the metals move during soil development, and also their ability to move to plant roots prior to absorption. Complexes between the trace metals and organic chelating compounds, often produced by microbial action, are especially important, and their rates of formation, of transport and of decomposition are being studied.

Toxic heavy metals are often present in sewage sludge used as an organic manure, and the behaviour of these metals determines whether they are a pollution hazard. Very similar chemical principles govern these and the plant nutrient trace elements, and sewage sludges have therefore been studied by similar methods.

Relations between 'available' and total contents of trace elements in different soil series and geological formations are also being investigated.

Soil development. The process of soil development is very slow, and cannot be observed in action. The 'layering' seen in soils can result either from soil-forming processes, or from a parent material which is itself deposited in

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layers. We use mineralogical techniques to distinguish initial non-homogeneity in the parent material, and investigate the remaining changes caused by weathering and soil formation. The 'brick-earth' soils in south-east England, glacial deposit soils and brown earths developing on steep slopes in west Britain have been examined in this way.

Wind-blown material, loess, is especially important since it improves the properties of soils which otherwise would be difficult to manage, and its effects and distribution are being studied.

Soil types and crop yields. The relative suitability of different soil types or series for crop growth is of great interest. There are wide yield differences between different fields and farms, and we must determine how much of this large variation results from soil type, how much from management and how much from the interaction of these. Detailed field experiments on different soil types measuring and testing a number of variables such as water supply, disease and physical properties may give an understanding of the mechanisms which determine the local yields.

As part of this work, we are cooperating in the making of simulation models of the winter wheat crop, and studying how the yields obtained by efficient farmers are affected by soil type.

Soil variability. Soil is not a homogeneous material and it varies both vertically and laterally at a wide range of scales. New methods of spatial analysis are being applied to describe this variation so that we can understand the various processes that have brought it about and do experiments on such heterogeneous material more efficiently.

Fertilisers and plant disease. We study the relationships, some beneficial and some harmful, between plant nutrients and diseases of farm crops in collaboration with the Plant Pathology Department.

Analytical methods. All our work involves analyses of soils and plants, and we use modern automated equipment including emission and absorption flame spectrophotometry. New methods and new equipment are constantly being developed and tested.

STATISTICS DEPARTMENT

The Statistics Department has its origin in the appointment of R. A. (later Sir Ronald) Fisher in 1919 to study the accumulated results of the Rothamsted Classical Experiments. Fisher soon realised the need for improved statistical techniques over the whole range of agricultural and biological research, and the groundwork for modern statistics was laid by him during the 1920s and 1930s. Under F. Yates, who retired in 1968, the size and responsibilities of the department expanded considerably and now, besides providing a statistical service for Rothamsted, it provides advice and assistance for workers at many other research stations both at home and overseas. The department also co-operates with the Agricultural Development and Advisory Service (ACAS) in designing experiments and surveys and provides numerical analyses of the results.

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Design and analysis of experiments. The efficiency of an experiment can be measured by the accuracy with which the effects of interest can be determined. Good design can greatly increase that efficiency, and so lead to better use of experimental resources. Many important ideas in the theory of the design of experiments came from Rothamsted, and now find application in all branches of experimental science. The department is involved in the planning of field experiments on the Station, and provides a service for the subsequent handling and analysis of the data they produce.

Because the results of crop experiments on a single site, such as Rothamsted, may not be typical of results of comparable experiments done elsewhere, an important activity is the design and analysis of series of experiments done at experimental and commercial farms in different parts of the country. This work is done jointly with ADAS. With careful planning these produce much more reliable information for advising farmers than does an experiment at a single site. As well as giving estimates of average treatment effects for a range of sites and seasons, the aim is to explain and, if possible, predict differences in effect from site to site from records of other environmental factors not under test.

The design and analysis of animal experiments produces problems associated with allowing for the effect of previous feed regimes on subsequent ones, and with making the best use of scarce, but variable, material. This work is another part of the statistical service we give to ADAS.

Design and analysis of sample surveys. Survey techniques, nowadays so familiar in the fields of public opinion and market research, have for many years had important application in agriculture. They are used to study the activities of farmers and to study what may be called the natural history of crop plants, and of animals and their parasites. The Survey of Fertiliser Practice (a continuing survey started in 1942) shows how farmers use fertilisers on different crops. This provides a guide to the type of advice likely to be most profitable to farmers, enables series of fertiliser experiments to be planned which are relevant to the differences between practice and current recommendations, and helps to put fertiliser use in a proper perspective in relation to other factors that can contaminate water supplies and the environment. Trends in use of fertilisers on individual crops are also used to forecast future fertiliser requirements.

Other investigations with which the department has recently been involved include surveys of the prevalence and severity of grass weed infestations in cereal crops and of the use of anthelminthics for cattle.

Much of this work is done jointly with ADAS and some in collaboration with the Agricultural Research Council Institutes and with other organisations such as the British Sugar Corporation and the Fertiliser Manufacturers Association.

Methodology. The application of statistical methods constantly exposes areas where current theory is deficient, and this provides the stimulus for the department's research work. We have an active interest in developing and using multivariate analysis, that is statistical methods of analysis that combine information on the many traits observable for any biological unit such as an experimental plot or an animal. Typical applications are in taxonomy,

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plant breeding, and the analysis of experiments involving many subjective judgements such as occur in assessing the qualitative aspects of foodstuffs.

We also collaborate with other departments in the development of mathematical models for the description of physical and biological systems. These aim to replace qualitative predictions about the behaviour of such systems with more precise quantitative ones.

Statistical computing. The many statistical calculations, of great variety, are almost all done by computer. To allow us to write down quickly the instructions required for a particular analysis we have developed special computer programs, each with a problem-oriented language. Thus the Genstat system provides a language specially constructed to help in specifying the analysis of designed experiments, multiple regression and its extensions, and multivariate analysis. Other programs are MLP, especially useful in the fitting of non-linear models to data; GLIM, which extends regression analysis to generalised linear models; and Genkey, which deals with the construction of diagnostic keys, such as occur in taxonomy. We are major users of the Rothamsted General Survey Program, originated by F. Yates when Head of the Department.

Some of the programs can be used interactively from a terminal to explore experimental data and associated models, and all have been written in a way that helps their conversion to run on machines other than our own. A licensing system covers their distribution to centres in Europe, North America, Australasia, and Africa.

Overseas work. The department contains a unit supported by the Overseas Development Administration, the function of which is to provide a service of statistical advice and computing to agricultural research workers in developing countries. We respond to continuing requests for help from all over the developing world and consultancy visits are paid to these countries from time to time.

LIBRARY

The Library, which comprises the Main Library, the Annexe, the Ogg Building library, the Bawden Building library, the storeroom and several departmental collections, contains about 80 000 volumes dealing with agriculture and scientific subjects, and is one of the foremost agricultural libraries.

Three-quarters of this stock consists of serial publications—about 7500 titles—of which over 2000 are currently received from all over the world.

Books are classified according to the Universal Decimal Classification, apart from the early works on agriculture, published between 1471 and 1840 in England, on the Continent and in America—a unique collection of about 3500 volumes—which are kept separate.

The collection of manuscripts relating to agriculture—letters, surveys, farm account books, field records, Lawes and Gilbert papers, etc.—covers more than five centuries and includes a copy of the *Treatise of Husbandry*, by Walter of Henley (1200–1283), written and illuminated in England on vellum during the fourteenth century.

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A collection of eighteenth- and nineteenth-century prints, mainly the bequest of the late Lord Northbrook, includes representations of livestock, scenes and agriculturists.

The maps, of which there are about 300 in the library, deal chiefly with soil, land use and geology.

The Library may be used by visitors on application to the Librarian. It operates a Xerox copy service, and copies of items in the Library can be supplied (at a moderate charge) to other libraries and individuals for the purpose of private study. Applications for copies should be made to the Librarian.

The following catalogues are maintained by the library: (*a*) Author Catalogue of Books and Pamphlets; (*b*) Subject Catalogue; (*c*) Author Catalogue of Scientific Papers Produced at Rothamsted, 1847– ; (*d*) Catalogue of Serial Publications; (*e*) List of Current Serials; (*f*) Catalogue of Early Printed Books on Agriculture, 1471–1840 (second edition 1940, supplement 1949); (*g*) Catalogue of Livestock Prints (1958). Rothamsted holdings are recorded in the *World List of Scientific Periodicals*, the *Union Catalogue of Periodicals in University Libraries* and the *British Union Catalogue of Periodicals*.

An on-line information retrieval service is available to staff and visiting workers.

THE COMMONWEALTH BUREAU OF SOILS

The Bureau, one of ten Commonwealth Agricultural Bureaux, was established at Rothamsted in 1929. Administratively and financially the Bureau is distinct from the Station, but the two work closely together. The Director of the Station is Consultant Director of the Soil Bureau.

The function of the Bureau is to assist workers in soil science, primarily throughout the Commonwealth but also throughout the world.

Publications include:

Soils and Fertilizers—a monthly abstract journal covering the world literature of soil science, soil–plant relationships and the use of fertilisers.

Irrigation and Drainage Abstracts—a quarterly publication covering the world literature of water management and soil–plant–water relations.

Annotated Bibliographies on specific subjects.

Technical Communications—monographs on specialised topics.

Special Publications on subjects of general interest.

On-line information retrieval services are available through Lockheed/DIALOG, SDC/ORBIT and ESA/RECON.

The Staff List, Plan of Station, and up-to-date information on the work of the departments and changes in the field experiments occurring since this booklet was printed are to be found in the pocket of the back cover.

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ROTHAMSTED EXPERIMENTAL STATION

FIELD EXPERIMENTS

Classical

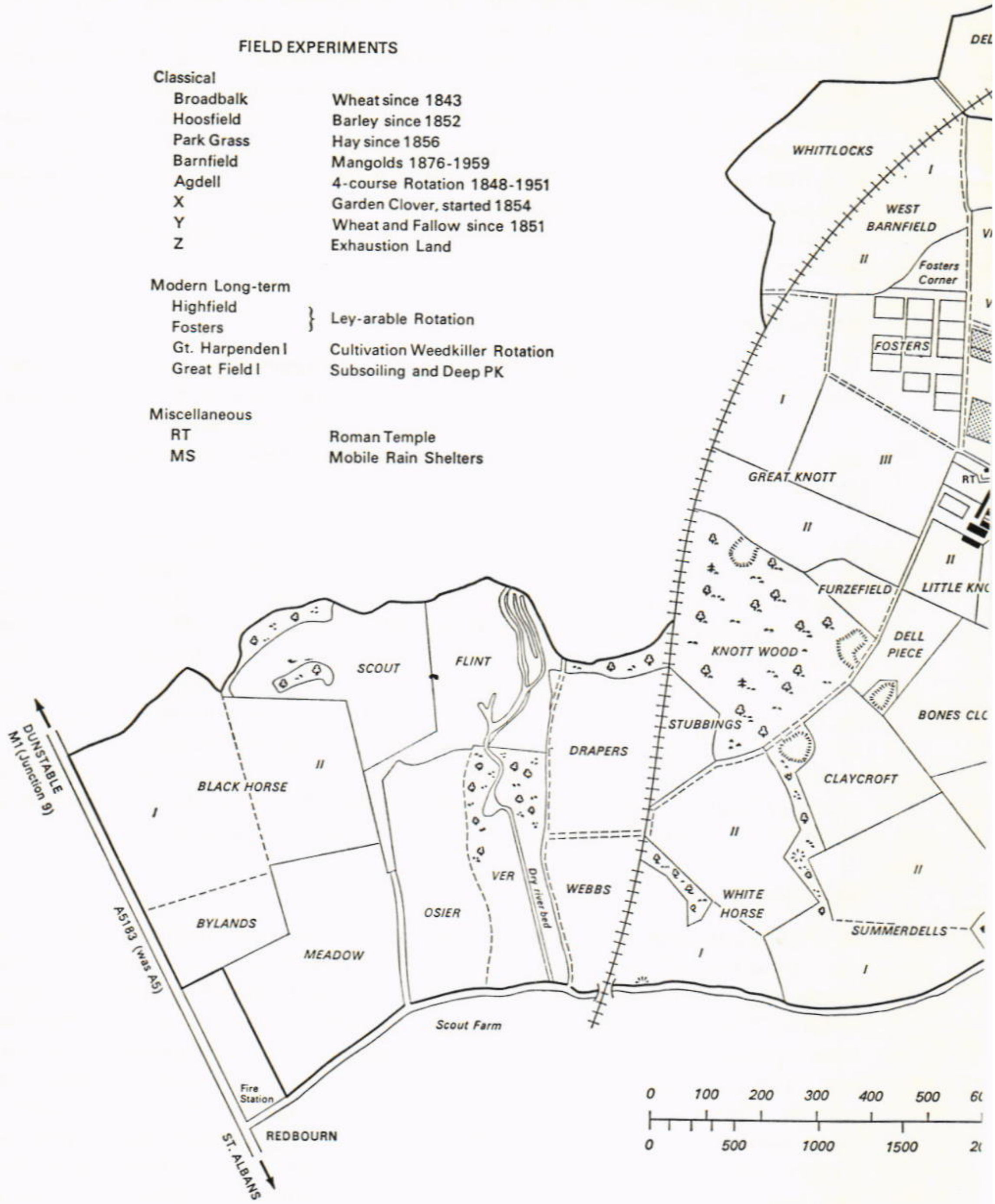
Broadbalk	Wheat since 1843
Hoosfield	Barley since 1852
Park Grass	Hay since 1856
Barnfield	Mangolds 1876-1959
Agdell	4-course Rotation 1848-1951
X	Garden Clover, started 1854
Y	Wheat and Fallow since 1851
Z	Exhaustion Land

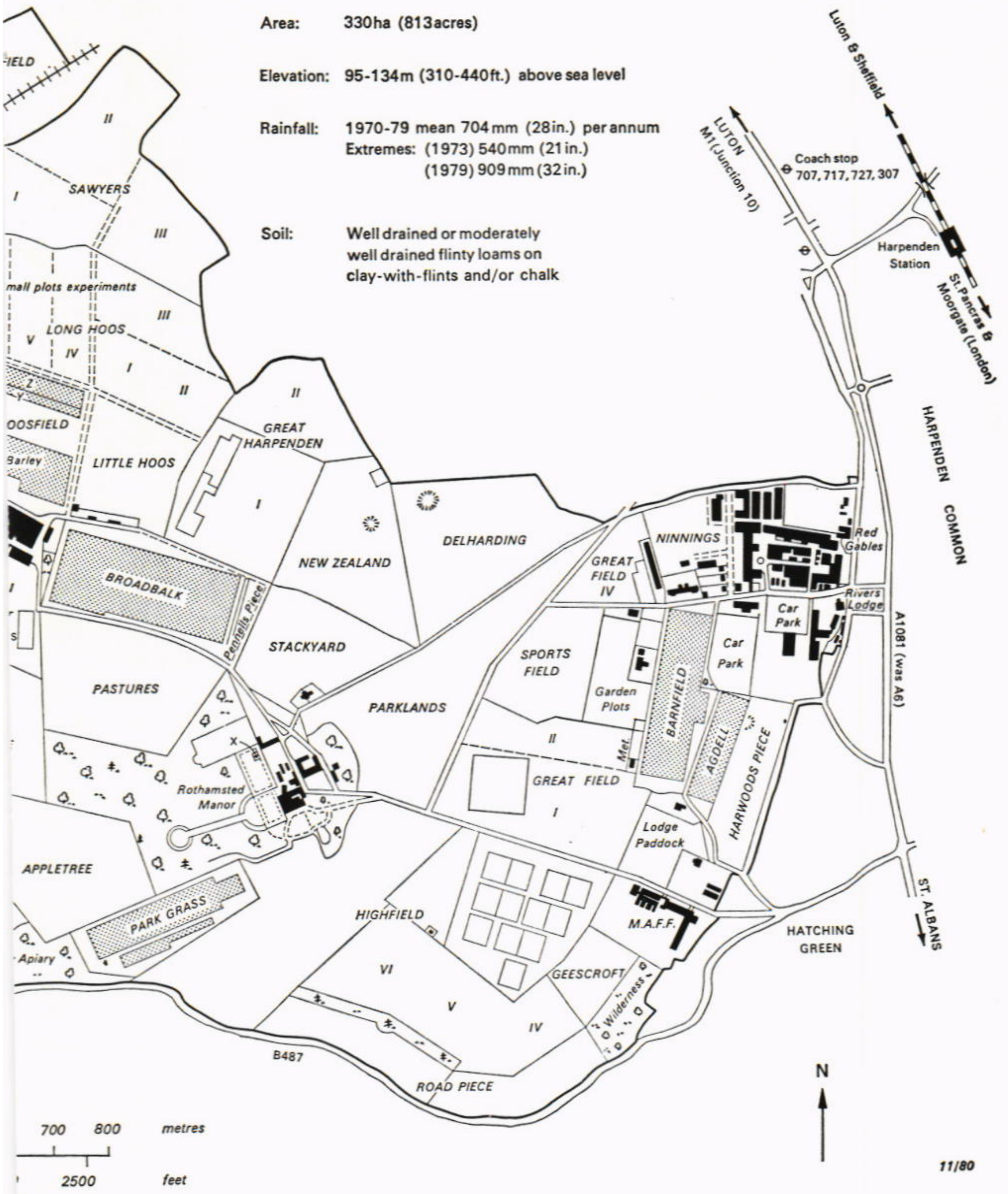
Modern Long-term

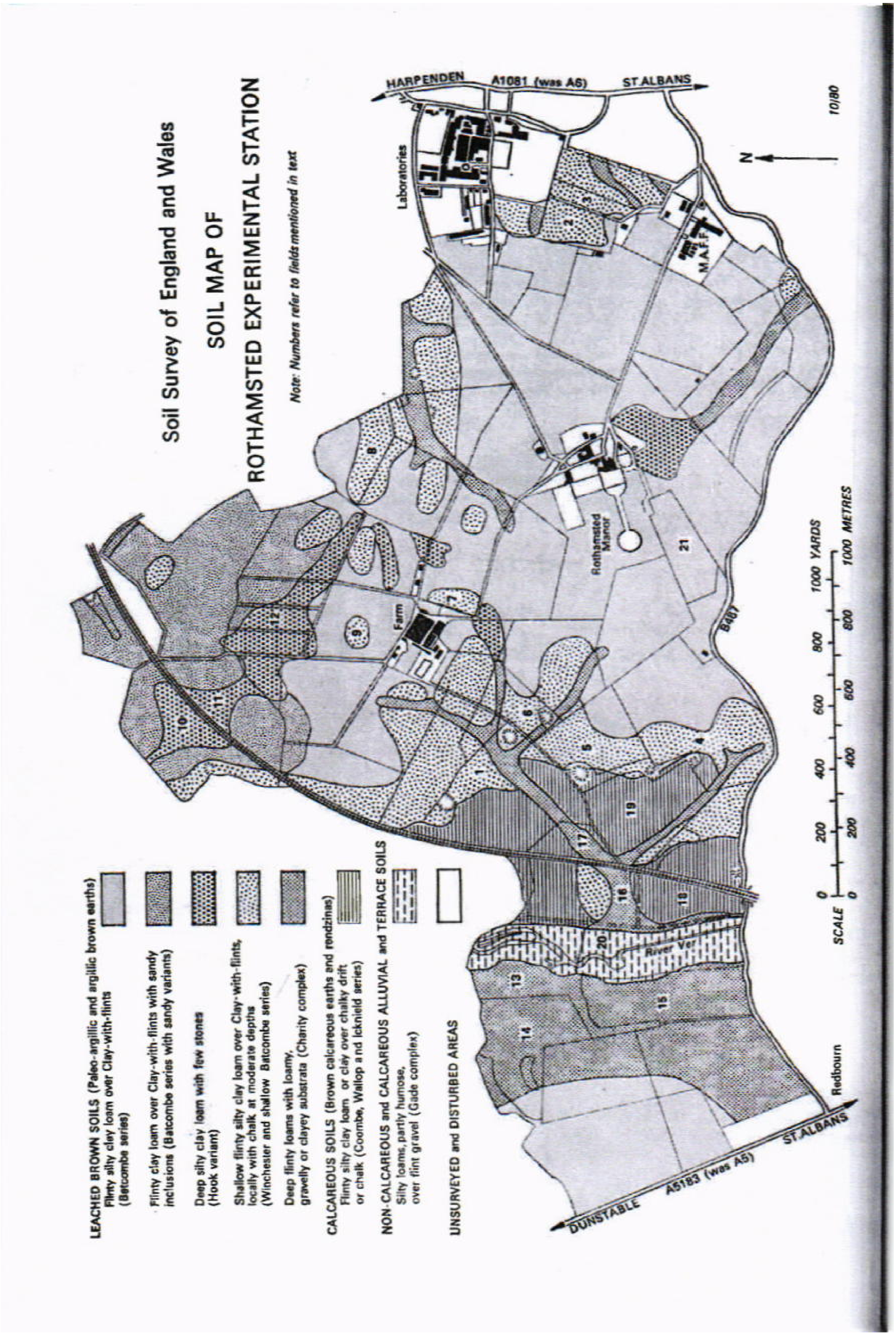
Highfield Fosters	} Ley-arable Rotation
Gt. Harpenden I	Cultivation Weedkiller Rotation
Great Field I	Subsoiling and Deep PK

Miscellaneous

RT	Roman Temple
MS	Mobile Rain Shelters




Area: 330ha (813acres)
Elevation: 95-134m (310-440ft.) above sea level
Rainfall: 1970-79 mean 704mm (28in.) per annum
Extremes: (1973) 540mm (21in.)
(1979) 909mm (32in.)
Soil: Well drained or moderately well drained flinty loams on clay-with-flints and/or chalk
Luton & Sheffield
LUTON
M1 (Junction 10)
Coach stop
707, 717, 727, 307
Harpenden Station
St. Pancras & Moorgate (London)
HARPENDEN COMMON
SAWYERS
LONG HOOS
LITTLE HOOS
GREAT HARPENDEN
NEW ZEALAND
DELHARDING
BROADBALK
Pennells Piece
STACKYARD
PASTURES
PARKLANDS
SPORTS FIELD
Garden Plots
BARNFIELD
AGDELL
HARWOODS PIECE
NINNINGS
GREAT FIELD IV
Red Gables
Rivers Lodge
Car Park
Car Park
A1081 (was A6)
Rothamsted Manor
GREAT FIELD
Met.
Lodge Paddock
APPLETREE
PARK GRASS
Apiary
HIGHFIELD
M.A.F.F.
GEESCROFT
Wilderness
HATCHING GREEN
ST. ALBANS
B487
ROAD PIECE
N
700 800 metres
2500 feet
11/80


Soil Survey of England and Wales
SOIL MAP OF
ROTHAMSTED EXPERIMENTAL STATION
Note: Numbers refer to fields mentioned in text
LEACHED BROWN SOILS (Paleo-argillic and argillic brown earths)
Flinty silty clay loam over Clay-with-flints (Batcombe series)
Flinty clay loam over Clay-with-flints with sandy inclusions (Batcombe series with sandy variants)
Deep silty clay loam with few stones (Hook variant)
Shallow flinty silty clay loam over Clay-with-flints, locally with chalk at moderate depths (Winchester and shallow Batcombe series)
Deep flinty loams with loamy, gravelly or clayey substrata (Charity complex)
CALCAREOUS SOILS (Brown calcareous earths and rendzinas)
Flinty silty clay loam or clay over chalky drift or chalk (Coombe, Wallop and Icknield series)
NON-CALCAREOUS and CALCAREOUS ALLUVIAL and TERRACE SOILS
Silty loams, partly humose, over flint gravel (Gade complex)
UNSURVEYED and DISTURBED AREAS
HARPENDEN
A1081 (was A6)
ST ALBANS
Laboratories
M.A.F.F.
Rothamsted Manor
Farm
B487
River Ver
Redbourn
DUNSTABLE
A5183 (was A5)
ST ALBANS
N
SCALE
YARDS
METRES
10/80

ROTHAMSTED FARM AND THE FIELD EXPERIMENTS

THE SOIL (see Map on p. 42) Numbers in brackets refer to fields marked on accompanying soil map.

The soils are in various superficial or drift deposits, including Clay-with-flints, valley Head deposits and river gravel, over Upper Chalk with nodules and layers of flint.

The Clay-with-flints, containing angular flints and flint pebbles in a clayey matrix, is more than 6 m thick in places. It is weathered debris of older sediments (chiefly Reading Beds) irregularly mixed with variable amounts of Chalk residue (chiefly angular flints) under periglacial conditions. On lower ground it is replaced or covered by younger drift deposits containing flint and other material from the older formations, together with wind-borne silt (loess), mixed and re-arranged by down-slope creep (Head) or by stream action. Thin spreads of loess-like drift ('brickearth') also occur on the higher ground, partly mixed with the Clay-with-flints below and modifying the texture of the soil.

Beneath the Ver valley floor are layers of flint gravel and silty alluvium laid down by the river in recent times.

The soils in these variable deposits have been classified by the Soil Survey of England and Wales, and the accompanying map indicates the approximate distribution of the soil series and other units identified.

Leached brown soils (Paleo-argillic and argillic brown earths). The main soils, on Clay-with-flints and flinty valley deposits, contain no naturally-occurring calcium carbonate, any originally present having been removed by leaching. They have brownish weathered subsurface horizons, with evidence of downward movement of clay-size particles.

Soils of the Batcombe series, which have a silty surface layer over Clay-with-flints, occupy most of the plateau east of the Ver valley. The topsoil is a greyish brown flinty silty clay loam with some 20–28% clay. This usually overlies a brown friable horizon of similar texture, which passes into stiff, brighter brown or yellowish red clay with scattered flints at 30–60 cm below the surface, but in places the clay is just below plough depth. Drainage is somewhat impeded by the clay, as shown by varicoloured mottling, black manganiferous deposits and grey-coated cleavage faces at depths below 45–60 cm, but neither ditches nor field drains are necessary for ordinary arable cropping. Where the Clay-with-flints thins on valley sides and spurs, the Batcombe soils are often replaced by those of the Winchester series, which have a subsoil layer of unmottled reddish plastic clay with large black-coated flints, resting irregularly on chalk at depths of 30–120 cm. These soils, which occur irregularly in and around Knott Wood (1), are grouped on the map with shallow (eroded) Batcombe soils in which the clay subsoil starts within 30 cm depth. Those of the latter kind are well represented in Barnfield (2) and Agdell (3), and in Summerdells (4), Claycroft (5) and Dell Piece (6). Smaller

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patches, each with some topsoil containing more than 30% clay, are in Broadbalk (7), Great Harpenden (8) and Hoosfield (9).

Especially in the northern part of the farm, the Clay-with-flints includes discontinuous sandy layers or pockets. The subsoils there are correspondingly variable, patches of red or yellowish sandy loam to sandy clay alternating with stiff flinty clay, and the topsoils commonly contain much more sand and less silt than elsewhere, giving clay loam or sandy loam rather than silty clay loam textures.

The Batcombe soils apparently incorporate a thin spread of silty loess-like material, mixed with the underlying Clay-with-flints. Thicker silty accumulations occur sporadically on the plateau, especially in shallow depressions at valley heads, and give deeper 'brickearth' soils like the Hook series. Typical profiles have brown subsurface horizons of friable silty clay loam with few flints, passing into a firmer, mottled subsoil. The largest and most homogeneous area of this variant extends from Whittlocks (10) through West Barnfield (11) into Long Hoos (12).

The remaining originally acid soils, grouped as the Charity complex, are in valley drift. Like those on Clay-with-flints, they usually have distinct finer-textured subsoil horizons at various depths, but are all well-drained, and have friable, more or less flinty surface and subsurface horizons of silt loam or silty clay loam texture. The largest area occupies the gentle footslope on the western side of the Ver valley. In Flint (13), Scout (14) and Osier (15) fields, the soil is locally so gravelly that augering is impossible below about 30 cm. Elsewhere, sometimes within a few metres, the drift contains few stones in the upper 80 cm, giving deep brown silty soils of the Hamble series. East of the Ver, Charity soils occur in the minor valley extending through Drapers (16) and Stubbings (17) fields into Knott Wood (1). Here the brown flinty subsoil rests on chalky drift. In the minor valleys that head on the plateau, the soils incorporate 'field-wash', accumulated since the land was first cultivated.

Calcareous soils (Brown calcareous earths and rendzinas). These are well-drained soils, on chalky drift or directly on solid chalk, that retain residual calcium carbonate and are consequently alkaline. They occupy slopes in Drapers (16), Webbs (18) and White Horse (19) fields and in Knott Wood (1). Texture, flintiness and calcium carbonate content change considerably over short distances. Most have a brownish subsurface horizon, but in others (rendzinas) the topsoil rests directly on fragmented chalk.

Alluvial and terrace soils (Alluvial gley soils, humic-alluvial gley soils and argillic brown earths). The alluvial soils in Ver (20) and Flint (13) fields have dark, friable, surface horizons with up to 15% organic matter. Sharp lateral variations in subsoil character can be related to small variations in ground-surface level and in turn to depositional history. Slightly raised terrace-like areas have loose flint gravel directly below the topsoil. In depressions, including former water-courses and ponds, nearly black surface horizons pass into greyish silt loam with rusty mottling, which is locally calcareous and overlies gravel.

Soil analysis. In its natural condition most of the soil on the plateau is acid. No area of the farm has soil that has not been influenced by management; probably the most nearly 'natural' soil is that of the unmanured and unlimed

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plots of Park Grass (21), with pH of 5·0–5·5. The old practice of excavating the underlying chalk and spreading it on the surface of arable fields gave them small reserves of calcium carbonate, Fields that follow our usual rotation of crops are limed once in 7 years to maintain an average pH value of 7·0. A few areas are deliberately kept acid.

The Classical experiments (see below) provide extremes of depletion and enrichment of P and K. Typical amounts are:

Field	Treatment since about 1850*	In soil now (mg kg^{-1}) P	K
Agdell	Nil	2	90
	PK	10	170
Barnfield	Nil	23	180
	PK	64	640
Broadbalk	Nil	8	100
	PK	80	360
Hoos Barley	Nil	5	90
	PK	130	430
Park Grass	Nil	5	60
	PK	130	670

* Amounts applied and periods differ from experiment to experiment.
Note: P is $NaHCO_3$-soluble; K is exchangeable.

WEATHER RECORDS

The meterological enclosure is in Great Field. In addition to the measurements returned to the Meteorological Office, others are made that are specially needed for agriculture or for use with the field experiments.

The observations cover a long period: rainfall (since 1852), drainage through bare soil, 20, 40 and 60 in. deep (50, 100 and 150 cm) (since 1870), air temperature (since 1878), and sunshine (since 1891). Rain, drainage, temperature, sunshine and radiation are continuously recorded. Daily observations include temperature measurements in the soil, under bare soil and turf, at

TABLE 1

Rothamsted weather: 10-year averages 1970–79 (and 1976 temperatures and rainfall in brackets)

	Mean air temperature °C	Rain (mm) (1)	Drainage (mm) (2)	Evaporation (mm) (3)	Sunshine (hours)	Daily solar radiation $MJm^{-2}d^{-1}$ (4)
January	3·4 (4·9)	74 (27)	64	8	42	1·9
February	3·6 (3·9)	59 (26)	48	10	63	3·9
March	5·1 (4·5)	62 (18)	38	27	106	7·5
April	7·3 (7·6)	51 (22)	20	49	129	11·2
May	11·0 (12·1)	52 (22)	18	83	196	16·2
June	13·9 (17·2)	57 (17)	16	99	201	17·4
July	16·0 (18·5)	34 (42)	3	103	190	16·0
August	16·0 (17·5)	55 (9)	14	91	180	13·4
September	13·5 (13·5)	58 (106)	20	69	148	10·1
October	10·2 (10·5)	56 (123)	31	34	103	5·7
November	6·1 (5·7)	75 (83)	53	16	74	3·0
December	4·6 (1·5)	71 (87)	58	8	45	1·7
Total or mean	9·2 (9·8)	704 (582)	383	597	1477	9·0
Equivalent to	49°F (50°F)	27·7 in. (22·9 in.)	15·1 in.	23·5 in.		

Notes—(1) 1/1000th acre (0·0004 ha) gauge.
(2) Through 20 in. (50 cm) bare soil.
(3) Open water. 6×6 ft (1·8×1·8 m) sunken tank.
(4) Total (Kipp).

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various depths down to 4 ft (1·2 m), at the tips of growing grass (grass minimum) and at screen height in the air (maximum, minimum, dry bulb and wet bulb).

Table 1 gives average weather at Rothamsted for the 10 years 1970–79. Some values for 1976 are included to illustrate an extreme deviation from the long-term pattern. A summary of the weather records for both Rothamsted and Woburn is given in the *Rothamsted Report for 1979*, Part 2.

THE FARM

The Rothamsted Home Farm of 100 hectares came under the management of Sir John Lawes in 1834. In 1843, and after, he assigned part of it to the field experiments on wheat, barley and grass now known as the Classical experiments. Although some land was sometimes in other occupation, Lawes always retained control of the experimental fields, which in his day were worked from farm buildings near the Manor House. These Classical Fields were made over on a 99 years' lease to the Lawes Agricultural Trust on its foundation in 1889, and have since been bought. More land has been acquired from the original home farm, and the adjoining Scout Farm, Redbourn, was bought in 1965. Today the estate, including woodlands, totals 330 ha of which 262 ha are farmed.

Classical experiments, long-term rotation experiments and crop-sequence experiments occupy the same sites every year. There are about 800 Classical plots which occupy about 16 ha. Rotation, crop-sequence and annual experiments total about 3000 large plots. In addition about 1600 plots are used for microplot experiments. One and a quarter hectares near the Laboratory, known as the Garden Plots, and approx. 9 ha on the farm, are used for small-plot experiments which cannot conveniently be done by farm equipment.

Organisation and staffing

The Working Party for Field Experiments plans the programme of field experiments. Detailed instructions are drawn up by the Field Experiments Section and passed to the Head of Farms. The Head of Farms, aided by two assistants at Rothamsted and a bailiff at Woburn, is responsible for the field work in connection with experiments and all matters relating to the farms. A team of recorders, responsible to the Head of Farms, is responsible for marking out the experiments, supervising all field operations on experimental plots, and recording yields. The Field Experiments Section maintains liaison between farm staff and the research workers. The Statistics Department analyses results of the experiments which are published each year.

The Farm staff consists of five tractor drivers, one general worker, a stockman/tractor driver, a mechanic and a building maintenance worker. The regular staff is supplemented by casual labour for potato picking and roguing wild oats in cereals.

Cropping

Of the 262 ha farmed, about 190 ha are under arable cropping. Much of the farm is worked on a 7-year rotation of two cereals, one break crop, two cereals, two break crops, to provide a choice of sites for cereals with different probabilities of attack by soil-borne pathogens. Several fields outside the rotation are not given P, K or lime. This is to provide sites

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where responses to applied P and K will be great, and where effects and interactions of soil pH can be measured. Some of this land is under grass and the rest is either fallowed or sown to wheat or oats, as it is now too acid to grow acceptable crops of barley or roots.

There are about 40 ha of permanent grass, some being low-lying river meadow and some unploughable because of trees. A number of experiments are sited on permanent grass, and a reserve is kept for future experiments.

Notes on crops

Wheat. The Rothamsted soil is well suited to wheat and about 50 ha are grown. Flanders is the standard variety on most experiments largely due to its good all-round disease resistance and proven reliability. However it is outyielded by new varieties and is being replaced by Hustler, Avalon and Brigand.

Wheat is generally grown as the first cereal after a break but some is grown after previous wheats for experimental requirements.

Black Grass (*Alopecurus myosuroides*) and Annual Meadow Grass (*Poa annua*) are a problem on some sites and chlortoluron ('Dicurane') is used in the autumn or isoproturon ('Hytane') in spring.

These chemicals are also effective against broad leaved weeds, often saving application of a hormone herbicide. Wild oats are, in most fields, few enough to allow hand roguing. Where there are too many for roguing, difenzoquat ('Avenge') has given excellent control.

Barley. About 90 ha are grown each year, about one-third autumn sown. The standard winter variety is Igri but other varieties are grown to meet experimental needs. Georgie has been the standard spring variety but is being replaced by Triumph. Seed of both winter- and spring-sown crops is usually treated with ethirimol ('Milstem') to control mildew (*Erysiphe graminis*) and crops may be sprayed with fungicides later in the growing season as necessary.

Early drilling of spring crops is an advantage particularly on the lighter land where seedbeds can dry out rapidly.

Beans. Beans (*Vicia faba*) are a useful break crop in the rotation as their husbandry requires no specialist machinery other than that used for cereals and herbicides, either simazine alone or as a mixture with trietazine, gives good weed control.

Most beans are spring sown as aphids can be controlled. Pirimicarb ('Aphox') is now used which is much less harmful to bees than demeton-S-methyl ('Metasystox') and more reliable than granules such as phorate ('Thimet').

Spring beans gave poor yields in 1970 and 1971 due to virus diseases and drought in 1975 and 1976 caused poor crops. Parts of the farm are infested with stem eelworm (*Ditylenchus dipsaci*) and this limits the frequency with which beans can be grown.

Some winter beans are grown as chocolate spot (*Botrytis* spp.) can usually be kept under adequate control with benomyl ('Benlate') repeated if necessary. There is a growing interest in the crop for experimental needs.

Potatoes. The area is restricted to about 12 ha each year by the scarcity of labour for lifting. Part of the area is planted with Foundation Stock,

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usually from the progeny of VTSC crops, to provide seed for the following year. This area is grown in isolation from other potato crops, and virus vectors, mainly aphids, are controlled by an application of a granular systemic insecticide at planting, and later by foliar sprays of insecticide, usually applied with a fungicide spray against blight (*Phytophthora infestans*). Strains of aphids resistant to demeton-S-methyl ('Metasystox'), the foliar-applied insecticide normally used, were found in 1976, and pirimicarb ('Aphox') has been used since.

All seed tubers are chitted in a temperature-controlled store and experiments are planted by a manually-fed 2-row machine or by hand. Non-experimental and seed crops are planted by automatic planter. Some fields are low in magnesium and a 10–10–15 fertiliser* containing 4.5% Mg is broadcast at 1900 kg ha^{-1} before planting, and the ground then levelled with a heavy spring-tine cultivator. Seedbeds are prepared by spike rotavator or rotary harrow.

An inter-row cultivator is used after planting and a further earthing up will be given in the season by a rotary ridger.

Weeds are controlled chemically by a pre-emergence spray of linuron, but paraquat may be added if weeds have emerged before spraying. All potatoes are sprayed regularly against blight and haulm is destroyed about a fortnight before lifting using a haulm pulverizer followed by spraying with sulphuric acid.

Lifting is normally by 2-row elevator lifter followed by hand picking. Transport to store is in 250 kg boxes. The stony soil is not really suitable for mechanical harvesting but a single-row harvester may be used if casual labour is short.

Potatoes are stored in an insulated building with provision for ventilation from a central duct with A-shaped on-floor laterals.

Potatoes are usually followed by winter wheat. Seedbeds are prepared by surface cultivation as ploughing buries the ground-keepers and encourages survival.

Oats. About 20 ha are grown as a 'break' in the rotation as they do not suffer from take-all (*Gaeumannomyces graminis*). Mostly winter oats are grown as they are usually ready before the spring barleys and this helps spread harvest as well as leaving the land clear for autumn-sown crops in reasonable time.

Only varieties resistant to stem eelworm such as Peniarth are grown.

Most autumn-sown crops are sprayed before emergence with methabenz-thiazuron ('Tribunil') to control annual grasses.

Sugar beet. The area of sugar beet grown is usually less than 0·5 ha and is grown in experiments only, as the autumn workload of potato lifting and drilling of winter cereals takes up all available labour.

Grass. There are about 65 ha grassland most of which is permanent or leys left down as long as they remain productive. One- or 2-year leys are sown to provide sites for fertiliser work which require a more uniform sward than that provided by older grass and short leys are sometimes used as a break from cereals.

* 10–10–15 and similar sets of figures indicate the percentages of N, P_2O_5 and K_2O respectively in the compound fertiliser.

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Most of the grass is grazed by cattle and the surplus cut for hay or silage. Except for the first cut on Park Grass all produce of grass experiments and the associated surrounds are ensiled. After weighing the samples all the remainder is direct cut using an additive. Usually three cuts a year are taken.

Irrigation

Water for irrigation is drawn by a submersible pump from a borehole 90 m deep into a 10^6 litre (1000 m^3) reservoir, lined with a butyl sheet. Water from the reservoir is pumped into 130 mm underground mains, fitted with hydrants. Much of the farm can be reached by 100 mm diameter portable aluminium surface pipes, connected to a convenient hydrant. Portable sprinklers can apply 25 mm of water in 4 hours to a maximum area of 0·8 ha at a time. As abstraction is limited to 27 000 m^3 experiments testing irrigation, and all potatoes, have priority for water supplies, and in recent dry years there has been little available for grassland.

On experimental plots, overhead oscillating spray lines are used to obtain a more uniform watering than the sprinklers, but are unsuitable for windy conditions, and there is growing interest in trickle irrigation for this purpose.

Livestock

Cattle. About 120 Hereford-cross steers are fattened each year. Yearlings are usually bought during autumn or winter, weighing about 300 kg. On arrival they are treated against lung intestinal worms and liver fluke (*Fasciola hepatica*). A systemic insecticide is used to kill warble fly larvae (*Hypoderma bovis* and *H. lineatum*). They are outwintered in sheltered fields with access to cover, and fed a ration of home-produced foods: silage, hay, barley straw and chat potatoes. Some of these cattle are finished on grass during the following year. Any not sold fat by late autumn are yarded and fattened on the above ration, supplemented by a home-grown concentrate based on cereals and beans.

Machinery

Because of experimental demands, a wide range of machinery is needed and it is not possible to use large units effectively. The farm is worked with eight light and medium tractors. Ploughing is still the chief primary cultivation for spring-sown crops and is done with reversible ploughs to eliminate ridges and furrows which complicate the siting of plots. After potatoes and beans, and on some stubbles where there is no trash to bury, a chisel plough or heavy spring-tine cultivator is used.

In preparing seedbeds the aim is to avoid excessive soil compaction. Operations are kept to a minimum by using, where necessary, rotary harrows which can produce a seedbed in a single pass in difficult conditions. However, in the spring when there has been natural weathering a spring-tine cultivator will normally produce a suitable seedbed for cereals and beans.

Small cereal and bean plots are harvested with a combine harvester built for plot work and fitted with a compressed air cleaning device. Most large plots are harvested by 3 m cut machines, which also handle the non-experimental areas.

Much straw is baled and carted to avoid uneven residues on long-term experiments and to provide litter and food for stock. Where straw is burnt it is usually spread first.

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For harvesting grass plots, a forage harvester has been adapted so that herbage is delivered into a box, from which it can be raked and weighed. Grass is cut for hay with a flail mower to speed drying.

An increasing part of the field work of a number of departments involves spraying; a high clearance tractor, with row-crop wheels, is used to meet this demand on bean and potato crops.

Buildings

The first of the cottages and farm buildings were built in 1913, but most have since been adapted for new purposes and new ones added. There is an insulated potato chitting store with refrigeration equipment and fluorescent strip lighting, and an insulated potato store with air ducting which allows ventilation and cooling of stored potatoes. The grain plant has a bin storage capacity of about 700 tonnes. The bins are fitted with ventilated floors which permit in-bin drying, cooling and self emptying. An oil-fired 4 tonnes per hour continuous-flow drier is available if the moisture content of grain is greater than can be dried by cold air ventilation. An in-sack platform drier is used to dry small experimental batches of grain, beans, oilseeds, etc. There is a well-equipped farm workshop.

There is yard space for about 90 cattle, a covered silage clamp and barns sufficient to hold up to 400 tonnes of hay and straw.

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THE CLASSICAL EXPERIMENTS

Between 1843 and 1856 Lawes and Gilbert started nine long-term experiments; some of the plot treatments were changed during the first few years and one experiment was abandoned in 1878, but when Lawes died in 1900 eight experiments were continuing more or less as originally planned. These are now called the 'Rothamsted Classical Experiments'.

Their main object was to measure the effects on crop yields of inorganic compounds containing nitrogen, phosphorus, potassium, sodium and magnesium, elements known to occur in considerable amounts in crops and farmyard manure, but whose separate actions as plant foods had not been systematically studied. The materials used were ammonium salts and nitrate of soda (as alternative sources of nitrogen), superphosphate (at first made by mixing bones and sulphuric acid for each experiment) and the sulphates of potash, soda and magnesia. Farmyard manure was also included in most of the experiments. The inorganic fertilisers were tested alone and in various combinations. Nitrogen was often applied at two or more different rates.

Lawes and Gilbert recorded the weights of all produce harvested from each plot, and samples were kept for chemical analysis. These results, together with details of the quantity and composition of each fertiliser applied, enabled a balance sheet for the major nutrients to be compiled for each plot, and analysis of soil samples showed whether nutrients accumulated or diminished in soil. The installation of drains (one to each plot) in the Broadbalk wheat experiment in 1849 allowed the losses of nutrients by leaching into the subsoil to be estimated. No other large-scale field experiment in the world is known to have this feature.

The classical experiments gave results of immediate value to farmers planning their use of fertilisers and manures, but their value to farmers diminished as the contrasted processes of depletion and enrichment of nutrients went on, progressively reinforcing the effect of each annual application of the manures. Until about 1939 the best yields obtained on each experiment were roughly equal to the average yields of the same crops as grown on English farms, and the amounts of fertilisers given (especially the nitrogenous ones) were similar to those used by farmers. Since 1939 with better-yielding varieties and increased use of fertilisers English farm yields exceeded those of the Classicals, until the recent modifications.

The Classical experiments have been modified since Lawes's death, mainly in three periods. Sir Daniel Hall, in 1903–06, added a few plots to Broadbalk, Park Grass and Barnfield, mainly to test the combination NKNaMg (that is, all major nutrients except P) which was originally omitted from these experiments. Hall also started the first scheme of regular liming on Park Grass, the only Classical experiment where increasing soil acidity was adversely affecting some plots. (The others were on old arable fields and had received the traditional heavy dressings of locally dug chalk, a practice not followed on grassland.)

From 1957 several of the Classical experiments were modified to evaluate the effects of the annually repeated dressings of different combinations of nutrients. This was done by introducing new crops (often several crops grown side by side on each of the original plots, as on the Exhaustion Land, Barnfield and Agdell) and by subdividing the old plots to test new fertiliser treatments. These modifications, together with detailed analysis of the soil by several

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methods, gave much information on the value of the accumulated residues of the materials applied in the past.

On Broadbalk and Hoos Barley crop rotations were introduced in 1968; substantial areas of each experiment remained in the traditional crops. The rotations were:

Broadbalk: potatoes, spring beans, winter wheat.
Hoos Barley: potatoes, spring beans, spring barley.

Beans became seriously infested with stem eelworm (*Ditylenchus dipsaci*) and they were not sown after 1978. On Broadbalk the rotation is now

fallow, potatoes, wheat

and on Hoos Barley the whole area is in continuous barley. The crop rotations have shown the yields of wheat and barley that can be obtained when soil-borne diseases and pests are lessened by growing non-susceptible crops for 2 years.

Barnfield, formerly a Classical experiment with mangolds and sugar beet, is expected to be used for a new long-term experiment involving leys but the start has been delayed.

The other major change introduced in 1968 except on Park Grass is the replacement of sulphate of ammonia and nitrate of soda by a mixture of ammonium nitrate and calcium carbonate ('Nitro-Chalk'). Castor meal (except on one plot of Broadbalk) has been discontinued, but its residual value is assessed on Hoos Barley and Barnfield, Most of the applications of sodium (as sulphate or chloride) have been discontinued.

On Broadbalk and Barnfield magnesium is now applied as kieserite (rather than Epsom salts) every third year, except for certain plots.

The following accounts of the separate experiments include minor changes made recently, the varieties grown and some of the recent results.

BROADBALK WHEAT (see plan p. 54)

The first experimental crop was wheat sown in autumn 1843 and harvested in 1844. Every year since then wheat has been sown and harvested on all or part of the field. The treatments compared are organic manures (farmyard manure and rape cake, later replaced by castor bean meal) and inorganic fertilisers supplying the elements N, P, K, Na and Mg in various combinations. For the first few seasons the treatments varied somewhat but in 1852 a permanent scheme was established and this continued until 1967. In the early years the field was ploughed in lands by oxen (later by horses) and the crop from each plot was separately cut with sickles. After threshing, the weights of grain and straw were recorded and samples kept for chemical analysis. (Many of these samples are still available and some have been used in recent investigations as 'pre-pollution' standards.)

Now we plough Broadbalk with a tractor-mounted reversible plough (this eliminates gathering ridges and open furrows) and we harvest with a combine harvester taking only the central strip of each plot for yield and samples. The wheat seed is dressed with insecticide and fungicide and the growing crop is sprayed as necessary to control aphids and foliar fungus diseases.

Much hand-hoeing was done in the past. When this became impracticable strips of the field ('Sections') crossing all the plots at right angles were bare

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fallowed, mainly in a 5-year rotation of fallow with four successive crops of wheat. Now most weeds are controlled by chemical sprays but one Section (8) is kept without sprays.

Effective control of weeds by sprays has eliminated the need for bare fallowing and Sections 0, 1 and 9 have been in continuous wheat since 1952, 1967 and 1959 respectively. On Sections 2, 4 and 7 a crop rotation (potatoes, beans, wheat) was followed from 1968; this is now fallow, potatoes, wheat. Sections 3, 5, 6 are now in continuous wheat (fallow, wheat, wheat from 1968–79).

In his first Rothamsted paper, published in 1847, J. B. Lawes described the Broadbalk soil as a heavy loam resting upon chalk, capable of producing good wheat when well manured, Similar land in the neighbourhood farmed in a five-course rotation would yield about 22 bushels of wheat per acre. In weight this is about 1350 pounds (lb) or 12 hundredweight (cwt); in metric terms this yield is about 1500 kg (=1.5 metric tonnes) per hectare, usually written 1.5 t ha^{-1}. At present the plot that has received neither manure nor fertiliser since 1843 yields about 2.2 t ha^{-1} after continuous wheat, 3.2 t ha^{-1} after potatoes and beans. Where nutrients are plentifully supplied by farmyard

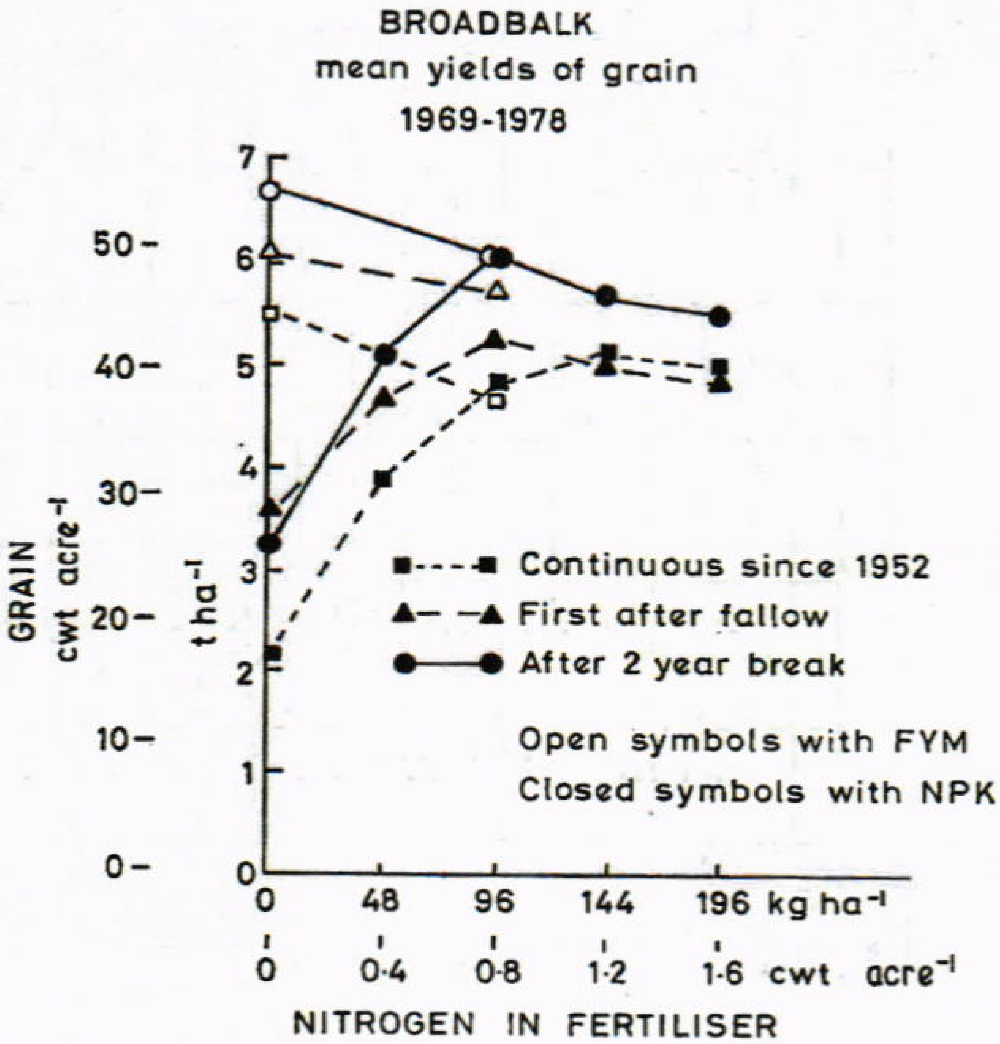

Fig. 1.

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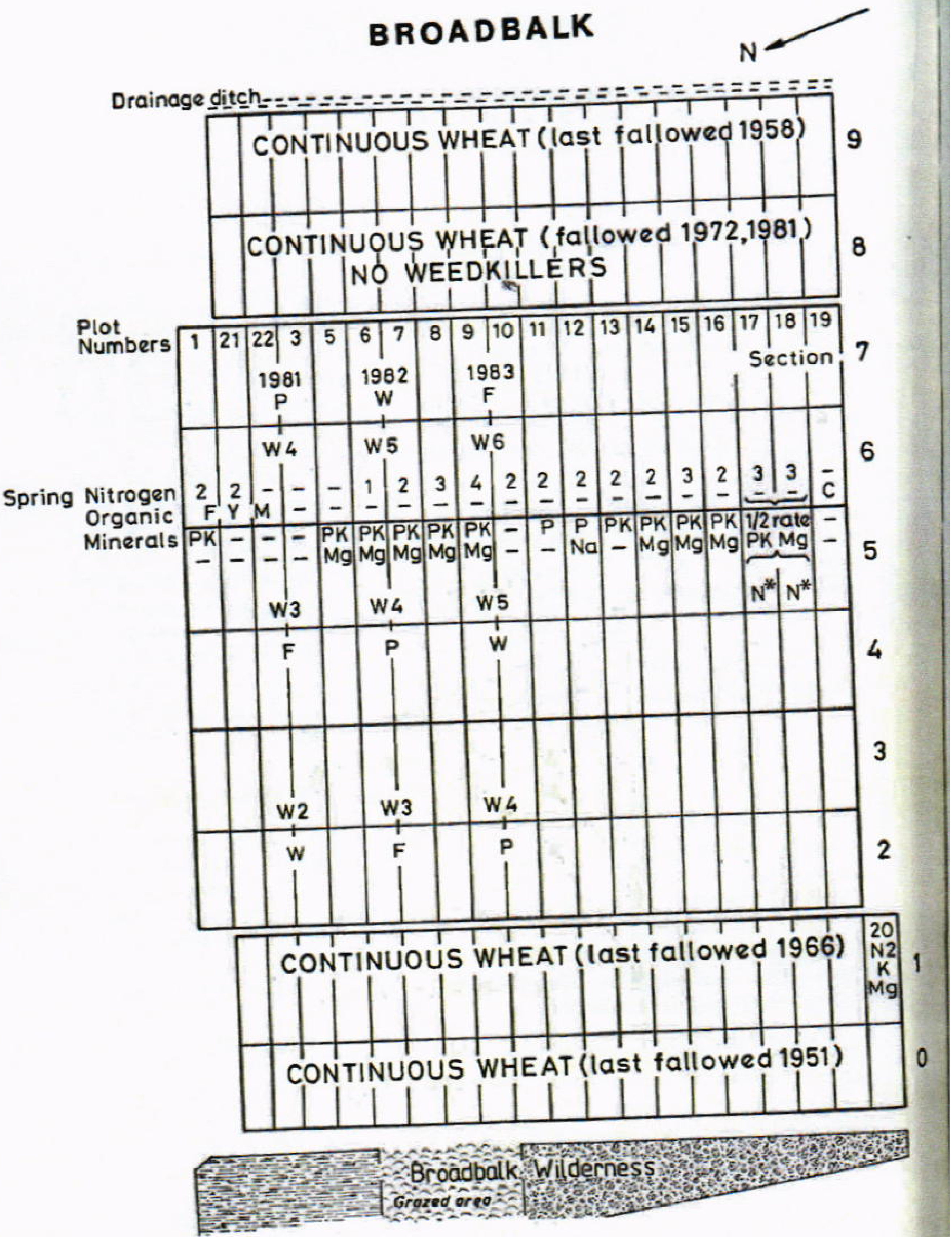

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manure (FYM) or fertilisers yields now average 5–6 t ha^{-1}, more than double the yield of the same treatments in the early years. These differences reflect the improved varieties, cultivations and control of pests, diseases and weeds that have been introduced on Broadbalk (and on English farms generally) in the last 130 years.

For most of the period of the experiment best yields from fertilisers (given by plots receiving PKNaMg and at least 96 kg N ha^{-1}) were equal to those given by FYM, but since the changes made in 1968 FYM has given more grain than fertilisers (see Fig. 1 and Table 2). On Section 0 (continuous wheat since 1952) the difference is 0.5 t ha^{-1}, after 1-year fallow 0.9 t ha^{-1}, and after the 2-year break (potatoes, beans) FYM has given about 0.3 t ha^{-1} more grain. The response curves (Fig. 1) show that more N applied in spring would not eliminate this difference. FYM plus 96 kg N has given consistently less grain than FYM alone; the weight of the extra straw given by the fertiliser N often causes the crop to lodge badly. On plots with fertiliser only, 144 kg N and 192 kg N give less grain than 96 kg N, except on Section 0, although there has been little lodging on these plots.

The 1-year fallow, introduced originally to control weeds, now acts mainly through lessening the inoculum of soil-borne fungi (especially the take-all fungus *Gaeumannomyces graminis*) and by allowing the accumulation of nitrogen available to the following crop. The 2-year break of potatoes, beans leaves very little take-all and, with 96 kg N applied, gives the best yields without FYM. Without applied N the wheat after beans is visibly

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Broadbalk (see plan on opposite page)

Cropping

Sections 0, 1, 3, 5, 6, 8, 9—continuous wheat (each section may be fallowed if necessary to control weeds).
Sections 2, 4, 7—three-course rotation: fallow (F), potatoes (P), wheat (W)

Dressings in autumn

All manures are applied annually to all sections except:

(i) Fallow receives no 'Nitro-Chalk'
(ii) Magnesium—see below.

Organic (applied before ploughing)

FYM	35 t ha^{-1} farmyard manure (from bullocks) (14 tons acre^{-1})
C	Castor meal (about 5% N) to supply 96 kg N ha^{-1} (about 1·9 t meal ha^{-1} or 15 cwt acre^{-1})

Minerals (applied before ploughing)

P	35 kg P ha^{-1} as granular superphosphate (19% P_2O_5) (0·6 cwt P_2O_5 acre^{-1})
K	90 kg K ha^{-1} as sulphate of potash (50% K_2O) (0·9 cwt K_2O acre^{-1})
Na	35 kg Na ha^{-1} as sulphate of soda (14% Na) to plot 12 only
Mg	30 kg Mg ha^{-1} as kieserite (16·8% Mg) to plot 14 only
	35 kg Mg ha^{-1} as kieserite every third year (1980, 1983) to other plots

Residual

Na	15 kg Na ha^{-1} to plots 5, 6, 7, 8, 9, 15, 16, 20 (and at 7·5 kg Na ha^{-1} to plots 17, 18) discontinued 1974

Nitrogen

N1*	48 kg N ha^{-1} as 'Nitro-Chalk' in autumn to plots 17 and 18 in alternate seasons (to plot 18 for 1981 crop; not applied to potatoes)

Dressings in spring

1, 2, 3, 4 'Nitro-Chalk' supplying 48, 96, 144, 192 kg N ha^{-1} (about 0·4, 0·8, 1·2, 1·6 cwt N acre^{-1})

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TABLE 2

Mean yield of wheat grain (10 years, 1969–78) and potatoes (total tubers, 10 years, 1969–78) all in t ha^{-1}

Plot	Treatment	Wheat: After fallow	Wheat: After 2-year break	Wheat: Continuous since 1952	Potatoes
3	None	3·0	2·8	1·8	10·5
5	PK(Na)Mg	3·6	3·3	2·2	15·3
6	N1PK(Na)Mg	4·7	5·1	3·9	24·8
7, 16	N2PK(Na)Mg	5·1	6·0	4·8	31·9
8, 15	N3PK(Na)Mg	5·0	5·8	5·0	36·4
9	N4PK(Na)Mg	4·9	5·5	5·0	40·6
10	N2	3·6	4·9	2·6	9·7
11	N2P	3·6	5·2	3·6	8·1
13	N2PK	4·7	6·0	4·9	23·2
12	N2PNa	4·0	5·5	4·6	11·4
14	N2P(K)Mg[1]	4·9	6·3	4·8	24·3
17, 18	N2+½(PK(Na)Mg)	5·3	6·2	4·6	28·6
22	FYM	6·2	6·6	5·5	37·6
21	FYM N2	5·7	6·1	4·7	42·7
1	FYM N2PK[2]	5·7	6·0	—	33·1
19	C	5·2	5·3	4·1	19·4

[1] K applied since 1968
[2] Since 1968

deficient in N in spring (short and very pale green); comparison with the first crop after fallow shows that fallow leaves more N available than beans, and this is reflected in the yields of grain (Fig. 1). Where N is applied the difference in level of disease is dominant and the order of yields is reversed.

Organic matter in the Broadbalk soil

As the carbon/nitrogen ratios are uniform in different plots, the nitrogen percentages can be taken as indicating the relative amounts of soil organic matter. On plots not receiving farmyard manure the nitrogen contents have remained steady for a century since they were first measured in 1865. By that date plots receiving NPK fertilisers had a little more N than the unmanured and minerals-only plots, where there are less roots and stubble. On the FYM plot nitrogen increased, at first rapidly, then slowly. After a century, annual dressings of FYM had more than doubled the amounts of nitrogen and organic matter (see Table 3).

The introduction in 1926 of regular fallowing, with cultivations to kill weeds and no manures applied, decreased the organic matter, especially on the FYM plot. After the reintroduction of continuous wheat on Section 0 (last fallowed in 1951), the organic matter of the soil increased more than on sections periodically fallowed.

TABLE 3

Nitrogen % of Broadbalk soils 0–23 cm

Plot	Manuring	1865	1944	1966
3	None	0·105	0·106	0·099
5	PKNaMg	0·107	0·105	0·107
7	N2PKNaMg	0·117	0·121	0·115
22	Farmyard manure	0·175	0·236	0·251

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Micro-organisms in the Broadbalk soil

More actinomycetes and bacteria occur in the FYM plot than in the unmanured plot or plot 7 (NPKMg), both of which contain similar numbers. The FYM plot and the fertiliser plot contain similar numbers of fungi, more than in the unmanured plot.

Amoebae are fewer in the unmanured plot than in the FYM plot or plot 7; these last two plots contain about the same number of amoebae, though very different amounts of organic matter.

The nitrogen fixing bacterium *Azotobacter chroococcum* fluctuates in numbers; the average population is greatest in those plots that receive neither N fertiliser nor organic manure. Anaerobic nitrogen-fixing *Clostridium* spp. are more abundant than *Azotobacter*. Nitrogen-fixing root nodule bacteria for field beans (*Vicia*) and clovers are widely distributed but not abundant in Broadbalk soil and those for the medicks and Lotus are sparse; none seems to be much affected by manuring. The continuous wheat crop removes from the soil on plots 3 and 5 about 24 kg N ha^{-1} each year and a further 12 kg N ha^{-1} $year^{-1}$ are lost by leaching but despite this the level of N in the soil has remained almost the same since the beginning of the experiment (Table 3). Nitrogen is added in seed (*c.* 3 kg N ha^{-1} $year^{-1}$), rain (*c.* 5 kg N ha^{-1} $year^{-1}$) and by the dry sorption of ammonia (*c.* 13 kg N ha^{-1} $year^{-1}$) but the largest input appears to come from nitrogen-fixing blue-green algae growing on the surface of the soil between the wheat stems. In a year with average rainfall the algae growing on plot 3 were estimated to fix 19 kg N ha^{-1}. A number of free-living heterotrophic nitrogen-fixing bacteria have been found in Broadbalk soils but their contribution to the nitrogen economy of the arable sections is very small.

Weeds on Broadbalk

Weeds have been surveyed at intervals since 1843 and twice yearly since 1931, and the weed seeds in soil from selected plots have been estimated at intervals since 1925. Weed surveys have been discontinued; the following notes are a slightly modified version of those written in 1976 by Joan Thurston, who has since retired.

About 50 annual and ten perennial weed species occur in the field. Of these, each plot in Section 8 (which has never had herbicides) has its characteristic 10–20 species, determined by its treatment, and the ground is covered with weeds after harvest (except on plot 3). Some species, e.g. blackgrass (*Alopecurus myosuroides*) and corn buttercup (*Ranunculus arvensis*) occur on all plots, but others are associated with individual treatments e.g. legumes where minerals are applied but not nitrogen. In contrast, in the stubble of the cleanest sprayed plots there may be less than five species, represented by only one or two plants of each.

Wild oats (mainly *Avena ludoviciana* with some *A. fatua*) became very numerous on Broadbalk during the 1940s; the 1-year fallow was ineffective against them. Since 1943 they have been pulled by hand as they appear above the wheat; slowly but surely this has decreased the population and pulling is now a relatively short job. On Broadbalk *A. ludoviciana* (which germinates in winter) is much commoner than *A. fatua* (spring germinating), but in the spring-sown barley on the adjacent Hoosfield the wild oats are mainly *A. fatua*. Most annual weeds germinate mainly at specific times of the year, usually autumn and/or spring, and few species germinate throughout the

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year. The preparation of seedbeds at different times of the year for winter wheat and spring barley allows different species to survive.

Several species of perennial grasses spread in Sections 0 and 9 (continuous wheat) while grass-killing herbicides were not used, but did not increase on fallowed sections until 1964 when they too received herbicides that controlled most broad-leaved weeds. More recently aminotriazole has been applied to the wheat stubbles (except on Section 8). It has probably slowed down the multiplication of perennial grasses but has not controlled them because the interval between treatment and ploughing is too short for effective translocation through the whole rhizome system.

Weeds in winter wheat. The use of herbicides to kill broad-leaved weeds has severely decreased susceptible species e.g. common vetch (*Vicia sativa*) and corn buttercup, but no species has been eliminated. Black medick (*Medicago lupulina*) decreased only slowly because the reserve of seeds in the soil was replenished by plants that emerged after spraying and seeded before the stubble was ploughed. Common vetch, corn buttercup and black medick are not well controlled by the fallow because only about half of their seeds germinate during the first year after shedding. Knotgrass (*Polygonum aviculare*) and scentless mayweed (*Tripleurospermum maritimum*) were not controlled by MCPA but are controllable now that mixtures containing dicamba or ioxynil are used.

Terbutryne applied just after sowing has controlled autumn-germinating blackgrass and some broad-leaved autumn-germinating weeds, notably ivy-leaved speedwell (*Veronica hederifolia*) which seeds before the spring spraying and so is not controlled by it but does not persist long enough to control spring-germinating blackgrass which is abundant when very wet or very dry autumns have prevented germination at its usual season.

As nearly all blackgrass seeds germinate during the first year after shedding it is greatly decreased by fallow, except when a very wet season enforces dormancy. A year of fallow decreases scentless mayweed seeds in soil by a quarter. If wheat bulb fly kills many plants in the first wheat crop after fallow, the surviving seeds of blackgrass and mayweed give large plants in the gaps and the numbers of seeds at the end of the year at least equal the number before fallow. The use of seed-dressing against wheat bulb fly thus helps to control these weeds on Broadbalk.

Weeds in potatoes. Although spring planting destroys weeds from autumn- and winter-germinating seeds, the deep cultivations for ridging bring buried weed seeds to the surface where they germinate, giving a mixture of seedlings of autumn, winter and spring-germinating species. These are controlled by pre-emergence herbicide (linuron-paraquat mixture) but field horsetail (*Equisetum arvense*), which emerges at the same time as the potato shoots and is resistant to those herbicides, is not controlled. It proliferates more in potatoes than in winter wheat because potatoes offer very little competition at the early stages of its growth, whereas winter wheat, especially with N, overshadows the young horsetail shoots from the start. Horsetail increased in density on infested plots in the rotation despite hand-pulling in potatoes because beans also offered little competition during early growth. The number of plots infested with horsetail did not increase during the first two cycles of the rotation. Cultivations during the fallow year in the rotation fallow, wheat, wheat (now discontinued) checked but did not eliminate it.

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Pests on Broadbalk

The continuity of cropping and manurial treatments makes Broadbalk a valuable field for studying the effects of weather on the incidence of some wheat diseases and pests.

Insect pests. Wheat bulb fly (*Delia coarctata* Fall.) often caused severe damage to the wheat-after-fallow strip on Broadbalk. Bulb fly eggs are laid during the summer on bare soil and damage is caused by larvae burrowing into the young wheat shoots in the early spring. Yield losses are related to the ratio of plants to larvae, to the time of attack and to conditions for plant growth. The plots on Broadbalk deficient in potassium usually suffered most because the plants were less well developed and damage to the primary shoot often killed the whole plant on these plots. The damage may be minimised by sowing wheat early because well developed plants can withstand attack, but the effects on yield vary greatly with season.

Other insect pests cause damage only sporadically; these include cereal aphids, cutworms, wheat-blossom midges and the saddle-gall midge. Now that potatoes have been introduced to the rotations potato aphids occasionally cause concern. The incidence of these insects is monitored and pest outbreaks are recorded.

Broadbalk drains

In 1849 a tile drain was laid down the centre of each of the plots. The tiles, of the 'horseshoe and sole' type, 2 in. (5 cm) internal diameter, were laid 60 cm below the surface, and led to a 10 cm cross main, which conveyed the water to a ditch. The drains were not intended for experimental use, but in 1866 they were opened at their junctions with the main, and at each of these points a small pit was dug to catch the runnings from each plot. The classical analyses by Dr. A. Voelcker were on samples drawn in this way in 1866–68. The main was enlarged and set deeper in 1879, and in 1896 a bricked trench was made to give easier access to the outfalls. Analyses of the drainage provided important information on the losses of plant nutrients by leaching. The biggest loss from this calcareous soil was calcium carbonate, and it increased with increasing amounts of ammonium salts given to the plot. The loss of nitrate was considerable, and this also increased with the amount of ammonium salts added. Phosphate, although applied in water-soluble form, was almost completely retained, and the loss of potash, though appreciable, was small.

Some of the free-living nematodes of the Broadbalk soils are carried down in the water reaching the drains and can be caught on fine-mesh sieves at the outfalls. This has added to the knowledge gained more laboriously by taking soil samples and extracting the nematodes.

Other uses of Broadbalk

Broadbalk has for many years attracted the interest of scientists working in subjects that were not in the minds of Lawes and Gilbert when they planned the experiment. Because the soil of each plot is now in a virtually stable condition and cultivations and husbandry are changed as little as practicable the crops on Broadbalk offer especially good facilities for studying fluctuations of yield or of pests, diseases, etc., in relation to seasonal differences. For example, eyespot (*Pseudocercosporella herpotrichoides*) and take-all

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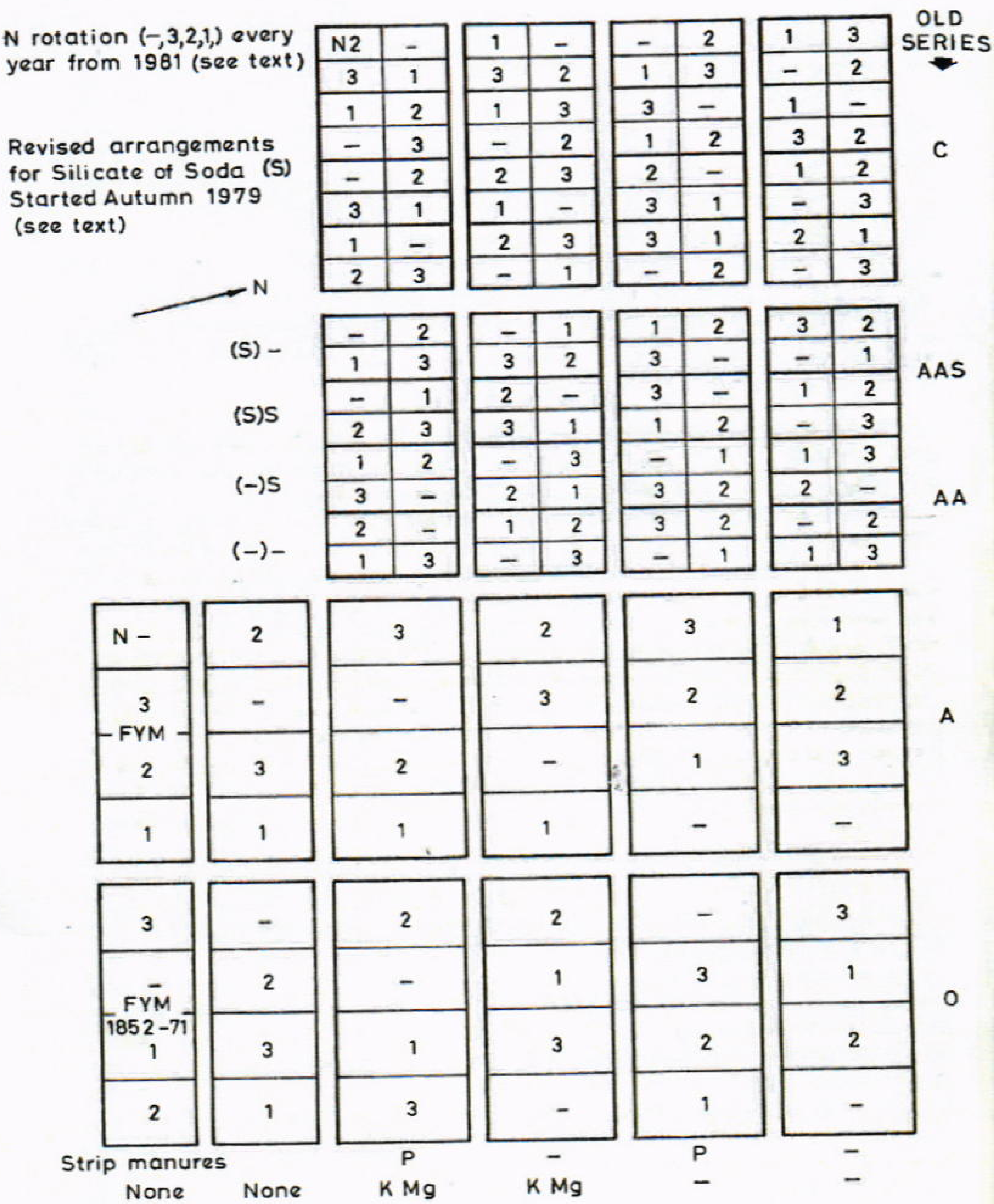
HOOSFIELD
Classical Barley Experiment, started 1852

Continuous Barley



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(*Gaeumannomyces graminis*), both soil-borne diseases of wheat, were studied by Mary Glynne for many years. H. F. Barnes studied the fluctuations in numbers of wheat blossom midges (*Contarinia tritici* and *Sitodiplosis mosellana*) for nearly 40 years. The statistical analysis of the relation between rainfall and yields of the Broadbalk plots was one of the first tasks of R.A. (later Sir Ronald) Fisher.

Current projects that use Broadbalk material include:

(1) growth analysis in relation to yield of wheat from season to season in standard soil conditions
(2) investigation of the uptake and losses of N fertiliser using ^{15}N as a tracer.

Material from the field is occasionally provided for workers outside Rothamsted.

BROADBALK WILDERNESS

In 1882 about 0·2 ha of the wheat crop on land unmanured for many years was enclosed by a fence at the end of the Broadbalk Field nearest the farm buildings, left unharvested and the land not cultivated. The wheat was left to compete with the weeds, and after only 4 years the few plants surviving were stunted and barely recognisable as cultivated wheat. One half of the area has been untouched; it is now woodland of mature trees about 20 m high, and leading species are ash, sycamore and oak. Hawthorn, now the understorey, is dying out. The ground is covered with ivy in the densest shade, and with dog's mercury, violet and blackberry in the lighter places. A recent winter gale blew down a tree of moderate size, creating the first appreciable gap in the canopy.

The other half has been cleared of bushes annually to allow the open-

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Hoosfield (see plan on opposite page)

Cropping
Continuous barley

Annual dressings

N1, 2, 3	'Nitro-Chalk' supplying 48, 96, 144 kg N ha^{-1} to barley (about 0·4, 0·8, 1·2 cwt N $acre^{-1}$).

The rates of N shown on the diagram are those applied to barley in 1981; they change cyclically, every year in order N3 following N^- following N1 following N2.

Minerals (applied before ploughing in autumn)

P	35 kg P ha^{-1} as granular superphosphate (19% P_2O_5) (0·6 cwt P_2O_5 $acre^{-1}$)
K	90 kg K ha^{-1} as sulphate of potash (50% K_2O) (0·9 cwt K_2O $acre^{-1}$)
S	450 kg ha^{-1} silicate of soda

Applied every 3rd year (1980, 1983 etc.)

Mg	35 kg Mg ha^{-1} as kieserite (15% Mg)

Organic

FYM	35 t ha^{-1} farmyard manure (14 tons $acre^{-1}$)

Residuals

Na	15 kg Na ha^{-1} as sodium sulphate discontinued in 1974 (applied with K and Mg)

Series treatments (discontinued 1968)

O	None
A	48 kg N ha^{-1} as sulphate of ammonia (0·4 cwt N $acre^{-1}$)
AA & AAS	48 kg N ha^{-1} as nitrate of soda
C	48 kg N ha^{-1} as castor bean meal

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ground vegetation to develop. This consists of coarse grasses, hogweed, agrimony, willow-herb, nettles, knapweed and cow parsley, but many other species are present in smaller numbers. The bushes that appear are mostly hawthorn, dog-rose, wild plum, blackberry, with a few maple and oak.

In 1957 this grubbed section was divided into two parts. The part farther from the woodland area was left unchanged, and the nearer part was mown several times during each growing season and the produce removed to encourage grasses. This management was continued for 3 years as a preparation for grazing; although the hogweed and cow parsley gave place to ground ivy, the grasses did not substantially increase. Starting in March 1960 sheep were put in to graze whenever the growth was sufficient. By 1962 perennial ryegrass and white clover had appeared, and they are now widely distributed. The ground ivy has almost gone, and the growth of the miscellaneous plants is much restricted.

The soil has gained much organic matter since the Wilderness was fenced off in 1882. Over the period 1883–1964, the net gain of nitrogen by the top 69 cm of soil from the grubbed part was 4·5 t ha^{-1}, and the corresponding gain of organic carbon 51 t ha^{-1}. The wooded and grubbed parts of the Wilderness accumulated carbon and nitrogen at almost exactly the same rates. By 1964, the Wilderness had gained more organic matter than the plot on Broadbalk receiving 35 t ha^{-1} of farmyard manure annually since 1843.

Legumes have been absent from the grubbed section of the Wilderness since 1915 and the nitrogen gains (equivalent to 49 kg N ha^{-1} $year^{-1}$) appear to come from rain, bird droppings, dry sorption of ammonia (15 kg N ha^{-1} $year^{-1}$) and from nitrogen fixation by bacteria in the rhizosphere of the perennial weeds. Acetylene reduction assays show that hogweed, hedge woundwort, ivy and ground ivy all support a nitrogen fixing flora which can, under wet conditions, fix as much as 0·5 kg N ha^{-1} day^{-1}.

Nitrogen gains in the wooded section are as yet unexplained.

HOOSFIELD BARLEY

This experiment, just north of the farm buildings, offers an interesting contrast with Broadbalk. On the Hoos experiment barley has always been sown in spring and there has been no regular fallowing. Indeed, in the 116 seasons 1852–1967, the area has been fallowed only four times.

A three-course rotation of crops (potatoes, beans, barley) was followed on small areas of certain plots from 1968 to 1978. The whole area is now cropped with barley each year.

The design of the experiment is of a factorial nature with strips running approximately east–west with the four combinations of

(1) None, superphosphate (P) and
(2) None, K Mg

and, on 'series' running north–south

(3) No nitrogen, N as sulphate of ammonia, N as nitrate of soda, N as rape cake (later castor meal) all at the same rate of N.

The nitrogen treatments to series are now discontinued, each of the original plots now being split into four sub-plots to test four rates of N (as 'Nitro-Chalk') in a rotating scheme.

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There are a few additional plots at the south and west, one of which has received FYM throughout the period of the experiment.

The edges of the plots are not at right angles, but at approximately 80°; this unusual arrangement conforms to the boundaries of the field and uses the available space effectively.

The barley on plots with incomplete manuring usually shows symptoms of deficiencies when about 10 cm high. As with all cereals, shortage of N causes the whole plant to be pale; the oldest leaves may turn yellow and die at the tips. K deficiency, especially obvious during dry springs, causes the early leaves to turn yellow and die at the tips; P deficiency sometimes produces a steely-blue tinge. Such symptoms, which soon disappear, are seldom shown by winter wheat on Broadbalk where differences of colour reflect mainly differences in supply of N.

The test of silicate of soda has now been modified so that the four combinations of

(1) None, silicate from 1980 and
(2) None, silicate 1862–1979

are all present each year. See *Rothamsted Report for 1979*, Part 1, 103, for more details.

PARK GRASS

The Park Grass Plots, laid down in 1856, are much the oldest surviving grassland experiment in Great Britain. They demonstrate in a unique way how continued manuring with different fertilisers affects the botanical composition and yield of a mixed population of grasses, clovers and weeds. The Park had already been in grass for several centuries when the experiment began; nevertheless, there are faint traces of plough furrows marking lands about seven paces wide. After more than 100 years, the boundaries of the plots are still sharp; the transition between adjacent treatments occupies 30 cm or less, showing that there is little sideways movement of nutrients in undisturbed soil.

The plots have been cut each year for hay all at the same time, although no single date can be suitable for all plots. For a few years the aftermath was grazed by sheep, penned on each plot and duly weighed. Since 1873 a second cut has been taken and carted green. Since 1960 yields have been calculated from the weights of produce from sample strips cut with a forage harvester (two per plot). Sub-samples are taken to estimate dry matter. At the first cutting the produce of the remainder of each plot is made into hay; this allows the return of seeds to the soil as in the past. At the second cutting the whole produce is carted green. The position of the sample strips differs from year to year.

The soil of Park Grass, in contrast to that of the nearby arable fields, contained little or no calcium carbonate when the experiment began; on plots treated with sulphate of ammonia, increasing acidity of the soil soon caused the sward to deteriorate. Lawes recognised this and made tentative applications of lime in 1883 and 1887, but regular liming was not begun until 1903. Then, and every fourth year until 1964, lime (originally burnt lime, recently calcium carbonate) was applied to the southern halves of most of the plots (see plan, p. 64). Except for plots 18, 19 and 20, a fixed amount was applied without regard to the different requirements of the several plots. From 1965

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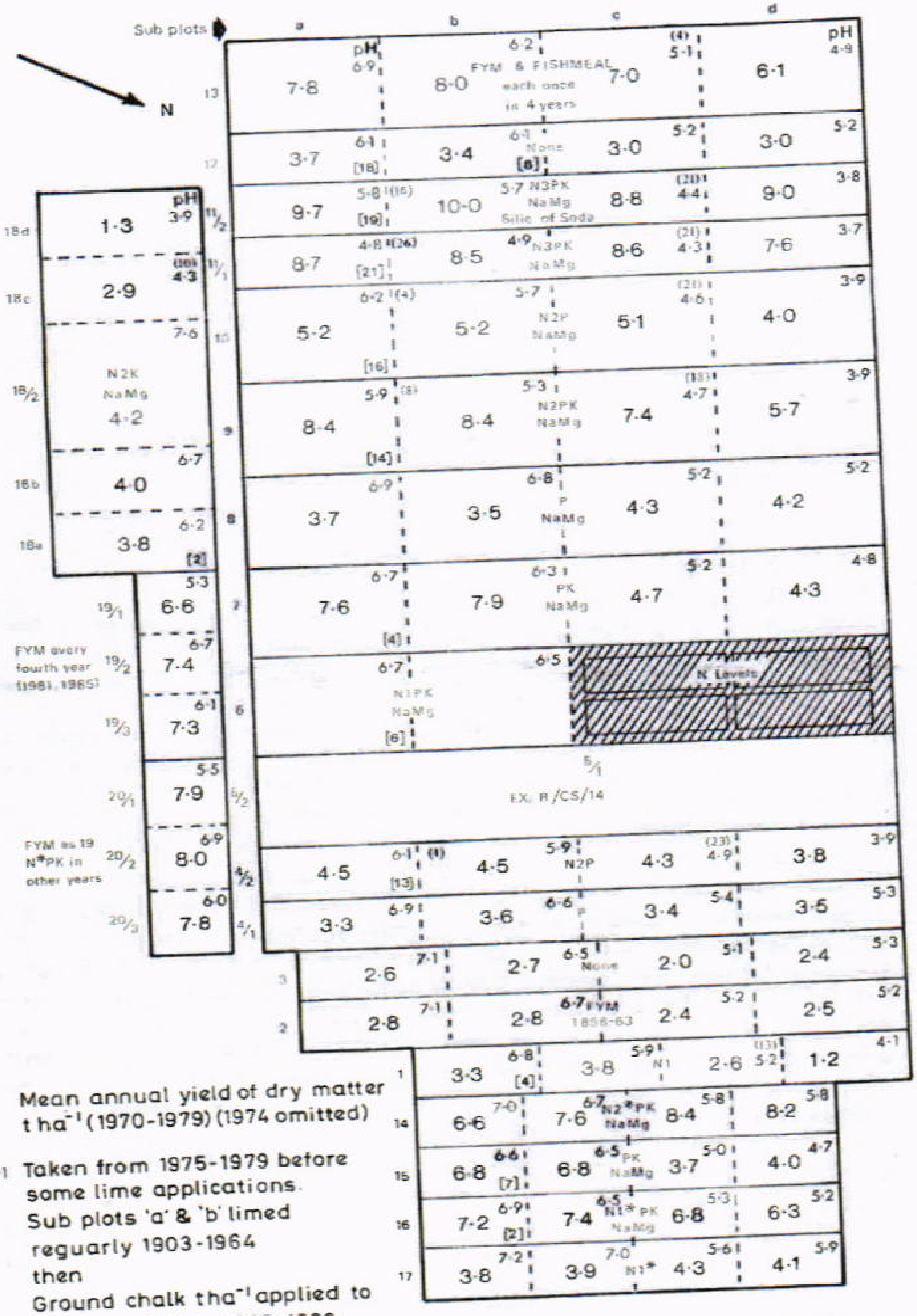
PARK GRASS

Hay each year since 1856



3·3 Mean annual yield of dry matter t ha⁻¹ (1970-1979) (1974 omitted)

pH 5·1 Taken from 1975-1979 before some lime applications. Sub plots 'a' & 'b' limed reguarly 1903-1964 then

(21) Ground chalk t ha⁻¹ applied to 'b' & 'c' subplots 1965-1968

[18] Ground chalk t ha⁻¹ applied to 'a' subplots and '12b' since 1968

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each half-plot on plots 1 to 18 was further subdivided. (At this stage the old plots 5–1, 5–2 and 6, whose treatments had not been constant throughout were given over to new experiments.) From 1965 only sub-plots 'd' remain unlimed. On the more acid plots, sub-plots 'c' (previously unlimed) now receive chalk calculated to give pH 5. Sub-plots 'b' (already limed) are chalked to give pH 6 and (from 1976) sub-plots 'a' to give pH 7.

The unmanured plots (3, 12) have the richest flora, with many red clover plants and broad-leaved weeds, but none grows vigorously, and yields are small. These swards are the nearest approximation to the state of the whole field in 1856. Lime alone or P alone (plot 4–1) has little effect. Plot 7 (PKNaMg) has a much stronger growth of legumes, including red clover (*Trifolium pratense*) and white clover (*Trifolium repens*), and meadow vetchling (*Lathyrus pratensis*); on this plot lime greatly increases the vigour and yield of the legumes. Plot 8 (PNaMg) is much poorer in meadow vetchling, and on this plot alone lime depresses yields.

With nitrogen, either as sulphate of ammonia or as nitrate of soda, yields are reasonable except on some of the unlimed ends. Plots 11–1 and 11–2 show the extreme effects of sulphate of ammonia. The unlimed end is dominated by Yorkshire fog (*Holcus lanatus*) and the mineral soil is covered by a layer of peat; earthworms are absent. The limed end has tall coarse species, false oat (*Arrhenatherum avenaceum*) and meadow foxtail (*Alopecurus pratensis*), and makes a poor hay, but the yield of dry matter compares well with much sown grassland. Nitrate of soda (14, 16, 17) supplies nitrogen without acidifying the soil; lime has little effect on these plots. Organic manures applied in alternate years (13) produce a well-mixed herbage, but yield is much less than from the best fertiliser treatments.

The most interesting feature of the experient since 1965 has been the change in the botanical composition of the swards of the sub-plots where lime has been applied to very acid soils. Red clover has occurred on most of these plots and is now well established on plots 1c and 9c. Fescues (*Festuca* spp.) have increased on plots given N1 and N2 with incomplete minerals (1c, 4–2c, 10c and 18c); tall oat grass (*Arrhenatherum elatius*) and cocksfoot (*Dactylis glomerata*) are now common on plots receiving N2 and N3 and

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Park Grass (see plan on opposite page)

Treatments (every year except as indicated)

Nitrogen (applied in spring)

N1, N2, N3	sulphate of ammonia supplying 48, 96, 144 kg N ha^{-1} (about 0·4, 0·8, 1·2 cwt N $acre^{-1}$)
N1*, N2*	nitrate of soda supplying 48, 96 kg N ha^{-1} (about 0·4, 0·8 cwt N $acre^{-1}$)

Minerals (applied in winter)

P	35 kg P ha^{-1} as granular superphosphate (19% P_2O_5) (0·6 cwt P_2O_5 $acre^{-1}$)
K	225 kg K ha^{-1} as sulphate of potash (50% K_2O) (2·2 cwt K_2O $acre^{-1}$)
Na	15 kg Na ha^{-1} as sulphate of soda (14% Na)
Mg	10 kg Mg ha^{-1} as sulphate of magnesia (10% Mg)
	Silicate of soda at 450 kg ha^{-1} of water soluble powder (plot 11/2)

Plot 20. Rates of manuring in years when FYM not applied: 30 kg N, 15 kg P, 45 kg K ha^{-1}

Organic (each applied every fourth year)

FYM 35t ha^{-1} farmyard manure (bullocks) (1981, 1985) (14 tons $acre^{-1}$)

Fish meal (about 6·5% N) to supply 63 kg N ha^{-1} (1979, 1983) (about 950 kg ha^{-1} meal or 850 lb $acre^{-1}$)

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complete minerals (9c, 11–1c and 11–2c) and also meadow foxtail and rough-stalked meadow grass (*Poa trivialis*) on N3 plots (11–1c and 11–2c). Smooth-stalked meadow grass (*Poa pratensis*) is now plentiful on all these sub-plots. Much mouse-ear chickweed (*Cerastium holosteoides*) and pignut (*Conopodium majus*) occur on sub-plots 1c and 18c and cow parsley (*Anthriscus sylvestris*) and hogweed (*Heracleum sphondylium*) on sub-plots 9c and 11–2c. Dandelions (*Taraxacum officinale*) are now present on all the recently-limed previously acid plots and occasional plants of many other broad-leaved weeds also occur. Increasing the pH to 6 on plots 9b, 11–1b and 11–2b has halved the amount of meadow foxtail but increased tall oat grass, expecially on 11–1b.

(The botanical notes above were written in 1976 by Joan Thurston who has since retired.)

The distributions in the soil of nodule bacteria for clover, *Lathyrus* and *Lotus* correspond closely to the distributions of their hosts in the different plots; neither medicks nor their nodule bacteria occur. Acid plots contain no nodule bacteria and liming increases numbers. On limed plots, N fertiliser has neither diminished the numbers nor altered the symbiotic effectiveness of the clover nodule bacteria.

ROTHAMSTED GARDEN CLOVER

The Garden Clover, pleasantly situated in the formal garden of the Manor House, has some claim to be the first micro-plot experiment. It is the simplest of the Classical Experiments, with (until 1956) only one plot, and that unmanured. Lawes, interested in the repeated growing of the same crop on the same land, found that red clover, however often resown on farmland, soon failed to give a useful yield. In 1854 he laid down this small plot in his garden. Yields were very large for the first 10 years averaging about 10 t dry matter ha^{-1}, probably because the soil was very rich in nutrients and because the soil-borne pests and diseases of clover were absent. Average crops were obtained over the next 30 years but thereafter yields showed a marked decline and there were several complete failures.

Between 1956 and 1972 the plot was sub-divided and a sequence of tests made of potassium, molybdenum, formalin, nitrogen and magnesium. N, K and Mg all increased yields, molybdenum and formalin did not. With N, P, K and Mg yields of about 6 t dry matter ha^{-1} were obtained in the year of sowing. The crop was usually severely damaged during the winter by clover-rot (*Sclerotinia trifoliorum*) and was re-sown each spring. From 1973 basal N, P, K and Mg were applied (corrective dressings were given to sub-plots which did not receive K and Mg in years of tests) and by 1975 the plot had returned to reasonable uniformity.

Between 1976 and 1978 aldicarb was tested (clover cyst nematode, *Heterodera trifolii*, was known to be present) and the variety Hungaropoly, believed resistant to clover-rot, was compared with the standard susceptible variety S.123. The combination of aldicarb with Hungaropoly gave yields up to 8 t dry matter ha^{-1} but winter survival remained poor.

The plot now grows Hungaropoly only, with basal aldicarb, and tests benomyl applied during autumn and winter. This treatment gave almost complete winter survival and a yield in 1980 of 14·6 t dry matter ha^{-1}, the largest recorded this century.

Clover nodule bacteria and their bacteriophages are abundant. Nodule bacteria for *Vicia* are sparse and those for *Lotus* and medicks absent.

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EXHAUSTION LAND (HOOSFIELD)

This area was cropped with wheat without manure from 1850 to 1855 when it was divided into five strips for a fertiliser test with continuous wheat given treatments similar to some of those on Broadbalk. This continued till 1875; potatoes were then grown from 1876 to 1901 with the strips halved to test ten manurial treatments repeated on the plots each year. Three of these treatments were the same as applied to the same plots under wheat.

TABLE 4

Number of annual dressings applied 1856–1901 and estimated amounts of P and K applied in FYM and fertiliser

	Plot number									
	1	2	3	4	5	6	7	8	9	10
	Number of dressings									
FYM	—	6	26	26	—	—	—	—	—	—
PK	—	—	—	—	—	—	42	42	17	42
P only	—	—	7	7	—	—	—	—	25	—
N	—	—	—	6	43	43	43	43	—	—
	Nutrients applied (kg ha^{-1})									
P	0	235	1260	1260	0	0	1410	1410	1410	1410
K	0	900	3920	3920	0	0	5040	5040	1570	5040

Table 4 shows the number of annual dressings given to these plots between 1856 and 1901 and estimates of the total amounts of P and K applied in FYM and fertilisers.

The potato experiment ended in 1901, and from 1902 to 1922 the plots were cropped with cereals without any manure; the yields of grain and straw were recorded in some years to measure the residual values of the manures applied to the potatoes. After 1922 cereal yields were not taken for many years, although differences between the plots were still visible. From 1940

TABLE 5

Mean yields of barley 1949–75 and recent soil analyses

Period	N kg ha^{-1}	Variety	Plots 1, 2, 5, 6 no P, no K	Plots 7, 8 residues of PK fertilisers 1856–1901	Plots 3, 4 residues of FYM 1876–1901
			Mean yields of grain, t ha^{-1}		
1949–53	63	Plumage Archer	1·6	2·9	3·0
1954–59	63	Plumage Archer	1·8	3·1	3·3
1960–63	63	Plumage Archer	2·0	2·6	3·1
1964–69	88	Maris Badger	1·7	3·6	4·3
1970–75	88	Julia	1·8	4·2	4·8
1976–79	None	Julia	0·9	1·6	2·1
	48		1·3	2·9	3·5
	96		1·4	3·0	4·0
	144		1·6	3·1	3·8
			Nutrients in air-dry soil and year of sampling		
N %		1974	0·102	0·100	0·124
P soluble in 0·5M-$NaHCO_3$, mg kg^{-1}		1951	7	21	27
		1965	6	12	18
		1974	2	8	12
K soluble in M-ammonium acetate, mg kg^{-1}		1951	74	121	106
		1965	88	122	114
		1974	69	89	87

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onwards a basal dressing of 63 kg N ha^{-1} as sulphate of ammonia was given to every barley crop. This increased the yield and accentuated the visual effects of the former manuring. From 1949 yields of barley have again been recorded. From 1964 to 1969 the variety Maris Badger was grown and given 88 kg N. Julia was introduced in 1970, also with 88 kg N and from 1976 fertiliser N has been tested at four rates (none, 48, 96, 144 kg N ha^{-1}) on sub-plots.

Table 5 shows yields and soil analysis for various periods from 1949 to 1975. Yields on plots without residues have fluctuated and new varieties there yielded no better than Plumage Archer. On plots with residues, Maris Badger and Julia, given 88 kg N or more, have yielded more than Plumage Archer, given 63 kg N. It is interesting that the difference in yield between plots with FYM residues and those with residues of PK fertilisers has been greater with the new varieties than with Plumage Archer. Plot 9, which received much less K than plots 7, 8 and 10, nevertheless gave for many years the same yield of barley, suggesting that the important effects were from P residues. During the last few years, however, yields have been about 0·5 t grain ha^{-1} less than on plots 7, 8, 10; possibly K reserves on this plot are now critically small. The plots with residues of FYM and 96 kg N ha^{-1} now yield about as much grain per hectare as the average of all barley crops in England and Wales.

Although this experiment shows the prolonged residual value of phosphate, the extra amount taken up in the crops is only a very small fraction (0·5% per annum) of the total amounts applied last century.

The above effects were measured in barley. Effects on five other crops were studied in a series of micro-plots in 1957 and 1958, when the residual effects were measured against direct additions of P and K.

MODERN EXPERIMENTS

Most of the experiments on the Farm (about 170 in all) last only one season and cannot be described in this Guide. Modern long-term experiments include:

(a) the two Ley-Arable experiments started 1949, now modified to continue studies of changes in soil organic matter due to different cropping systems, and to study the soil-borne diseases of wheat in relation to past cropping

(b) the Cultivation Weedkiller experiment started 1961, now modified to compare methods of cultivation and sowing (including direct drilling) for continuous winter barley

(c) the Reference Plots of the Soils and Plant Nutrition Department which show the responses of a range of crops grown in rotation to fertilisers and farmyard manure and provide material for chemical analysis and calculation of the nutrients removed in the crop. Additional plots have tested applications of trace elements, which usually produce no increase of yield

(d) several experiments which explore the effects of loosening the subsoil with or without the addition of P and K fertilisers below plough depth.

In addition there are several complex multidisciplinary experiments (on a fresh site each year) designed to assess the maximum yields of winter wheat and winter barley when every known limitation to yield (pests, diseases,

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drought, nutrient deficiencies) is eliminated. The factorial nature of these experiments gives measures of the loss of yield caused by omitting one or more of the inputs, some of which are admittedly uneconomic.

WOBURN

Experiments began on the farm at Woburn in Bedfordshire in 1876, under the auspices of the Royal Agricultural Society of England, and Rothamsted assumed responsibility in 1926. The farm is not owned by the Lawes Trust but is rented from the Bedford Estates. Over most of the farm the soil is a sandy loam, derived from the Lower Greensand, differing greatly from the Clay-with-flints at Rothamsted, and many of the problems in arable agriculture differ at least in degree from those on the heavier soil. Woburn still fulfils an original purpose, to duplicate experiments done at Rothamsted on a different soil type, but for many years work has also been done on problems especially important in light-land farming, such as acidity, nitrogen deficiency, poor soil structure, and small water-holding capacity. Experiments on green manuring, ley farming and organic manuring have for long been major parts of Woburn's programme; work with irrigation began there in 1951. Since 1974 substantial increases in yield of wheat, barley and sugar beet have been obtained from subsoiling alone and of potatoes, barley and sugar beet from incorporating PK fertilisers in the subsoil. Reasons for these increases are being sought.

The light soil of most of the Woburn farm is favourable to nematodes, both the free-living and cyst-forming types. Experiments, mostly long-term, are being done on potato cyst-nematode, both species of which (*Globodera* (formerly *Heterodera*) *rostochiensis* and *G. pallida*) occur at Woburn. The complex relations between the species, and how this is affected by nematicides and different varieties of potatoes, some with a degree of resistance, are being studied in long-term experiments. Other experiments deal with population dynamics and seek economic means of control by chemicals. There is evidence that potatoes at Woburn occasionally suffer appreciably from other nematodes that do not form cysts. Growth and yield experiments on winter wheat at Woburn provide a useful comparison with similar, more detailed work at Rothamsted.

Cereal cyst nematode (*H. avenae*) is also studied. Other pathogens which are more prevalent in the Woburn soil than at Rothamsted are the fungi *Verticillium* (which attacks potatoes in conjunction with cyst nematode) and *Streptomyces scabies* (common scab of potatoes) and experiments test methods of control of both.

Some fields have a heavier soil derived partly from Oxford Clay, and about half is devoted to a long-term rotation experiment on cultivation and the effect of deeply incorporated PK.

Cropping and organisation

The farm totals 76 ha, the main arable crops being barley (18 ha), wheat (20 ha) and potatoes (8 ha). It is not easy to grow suitable break crops; beans and leys suffer from drought and sugar beet clashes with potato harvest. Some beans are grown on the heavy land and more recently winter oats have been introduced. Because of potato cyst-nematode part of the area of potatoes is planted with Maris Piper or more recently Cara which is

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resistant to *Globodera rostochiensis* but not to *G. pallida*, and stem-eelworm resistant varieties of oats are grown. Of 15 ha of grassland, about 8 ha are temporary grass, most being 1- or 2-year breaks in the rotation, and the rest is permanent grass.

The farm is staffed by a bailiff responsible for day-to-day organisation, and three tractor drivers, with two recorders responsible for marking out and applying treatments and recording yields from experimental plots.

Large experimental plots total about 1500 and the methods used are similar to those at Rothamsted. In addition about 1000 plots are used for microplot experiments.

The farm is well equipped with buildings. There is adequate storage for hay, straw and machinery, and there is an insulated potato store with a capacity of 200 tonnes.

Grain is dried in radially ventilated silos before being transferred to steel silos for storage. These are fitted with low-volume ventilation to allow cooling in suitable conditions, and permit storage at a higher moisture content than in unventilated bins. Total storage capacity is 180 tonnes.

About 40 cattle are yarded each winter. They are usually fattened off grass in the following summer but if grass is short in dry summers they may be transferred to Rothamsted.

SAXMUNDHAM

The East Suffolk County Council began experiments on permanent sites at Saxmundham in 1899. The work was continued by the National Agricultural Advisory Service from 1947 to 1964, when the Experimental Station, now only 3 ha, was placed under Rothamsted's control. The sandy-clay soil at Saxmundham contains about the same amount of clay as the Rothamsted soil, but is much more difficult to work and this difference in soil structure is being investigated.

The Station originally possessed two Arable Rotation experiments (I and II) started in 1899. The site of Rotation I is used to measure (i) the rate of removal of potassium by arable crops and grass and (ii) to measure benefits from part of the experiment where lucerne was grown between 1970 and 1976. The experiment also provides a site with a known history of manuring for an experiment on subsoiling and deep incorporation of PK fertilisers. Part of Rotation II has been used since 1965 for experiments on factors affecting the growth of winter wheat on poorly-structured soil. Between 1971 and 1976 yields of wheat grown continuously were as large at Saxmundham as at Rothamsted; poorer yields obtained before this may have been due to late sowing. The remainder of Rotation II has been used to establish a range of soils containing different amounts of soil phosphorus (ADAS Index 0 to 4). Yields and responses to fresh superphosphate have been measured for cereals and root crops grown at each soil P index. The site is now being used to measure the rate at which available P residues decay in this soil.

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SOME PUBLICATIONS AVAILABLE FROM ROTHAMSTED

The following are available from the Librarian:

REPORT, ROTHAMSTED EXPERIMENTAL STATION

From 1909 (annual, some are out of print). Prices upon application.

YIELDS OF THE FIELD EXPERIMENTS

Formerly called 'Numerical Results' . . . or 'Results' . . . published annually 1948 onwards. Prices upon application.

DETAILS OF THE CLASSICAL AND LONG-TERM EXPERIMENTS UP TO 1973

Two books—'Details . . . up to 1967' and a supplementary volume 'Details . . . up to 1973'. Price £1 each, sold separately.

THE PARK GRASS PLOTS AT ROTHAMSTED 1856–1949 Price £1.50.

BOTANICAL COMPOSITION OF THE PARK GRASS PLOTS AT ROTHAMSTED 1856–1976 Price £1.

THE BROADBALK WHEAT EXPERIMENT Up to 1968. Price £1.

SUBJECT DAY BOOKLETS (£1 each)

NITROGEN
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SOIL

THE MANOR OF ROTHAMSTED Price £1

The following are available from the Field Experiments Section:

(A complete list of visual aids is available on request. Prices of slide sets and cassettes are for 1981 and are subject to possible increase afterwards.)

SLIDE SETS

BROADBALK WHEAT EXPERIMENT

The effect of fertilisers on continuous wheat since 1843, a rotation of wheat, potatoes, beans and fallow and a natural regeneration from wheat to woodland is shown. Rothamsted. Complete with notes. 65 slides (2 × 2). Colour. £18 per set.

THE PARK GRASS EXPERIMENT 1976

On the effect of fertilisers and liming on the botanical composition of permanent grassland and on the yield of hay. (Miss J. M. Thurston, E. D. Williams and G. V. Dyke.)
Rothamsted. Complete with notes. 34 slides (2 × 2). Colour. £10 per set.

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CASSETTE FILM LOOPS

4 minute, colour, Technicolor cassettes. Standard or Super 8 suitable for projectors such as the THD MacMillan or Technicolor.
Price £15 each, complete with notes.

1. Weed Seed Survey—Techniques for assessment of seed dormancy using simple tools.
2. Scanning Electron Microscope—Preparation of specimens for, and operation of, the scanning electron microscope.
3. The Rothamsted Rhizobium Collection—Strains of nitrogen-fixing bacteria are preserved and kept in pure culture form.
4. The Ryegrass Mite—*Abacarus hystrix* is a vector of Ryegrass Mosaic Virus.
5. The Stem Nematode—*Ditylenchus dipsaci* is shown feeding.

Conversion Factors etc

1 metric ton or tonne (t) = 1000 kilograms (kg) = 0·984 ton
1 hectare (ha) = 10 000 square metres = 2·47 acres
1 tonne hectare^{-1} (t ha^{-1}) = 0·398 tons acre^{-1}
= 7·97 cwt acre^{-1}
= 892 lb acre^{-1}

Old units

1 bushel (bu) = 36·4 litres
1 quarter (qr) = 2 sacks = 8 bushels
1 bu wheat weighs about 29 kg (63 lb)
1 bu barley weighs about 25 kg (56 lb)
1 bu oats weighs about 19 kg (42 lb)
(1 British bushel = 1·03 US bushels)

Nutrients

To convert	Multiply by
P_2O_5 to P	0·436
K_2O to K	0·830

100 kg ha^{-1} = 89·2 lb acre^{-1} = 0·797 cwt acre^{-1} (i.e. 79·7 'units' acre^{-1})

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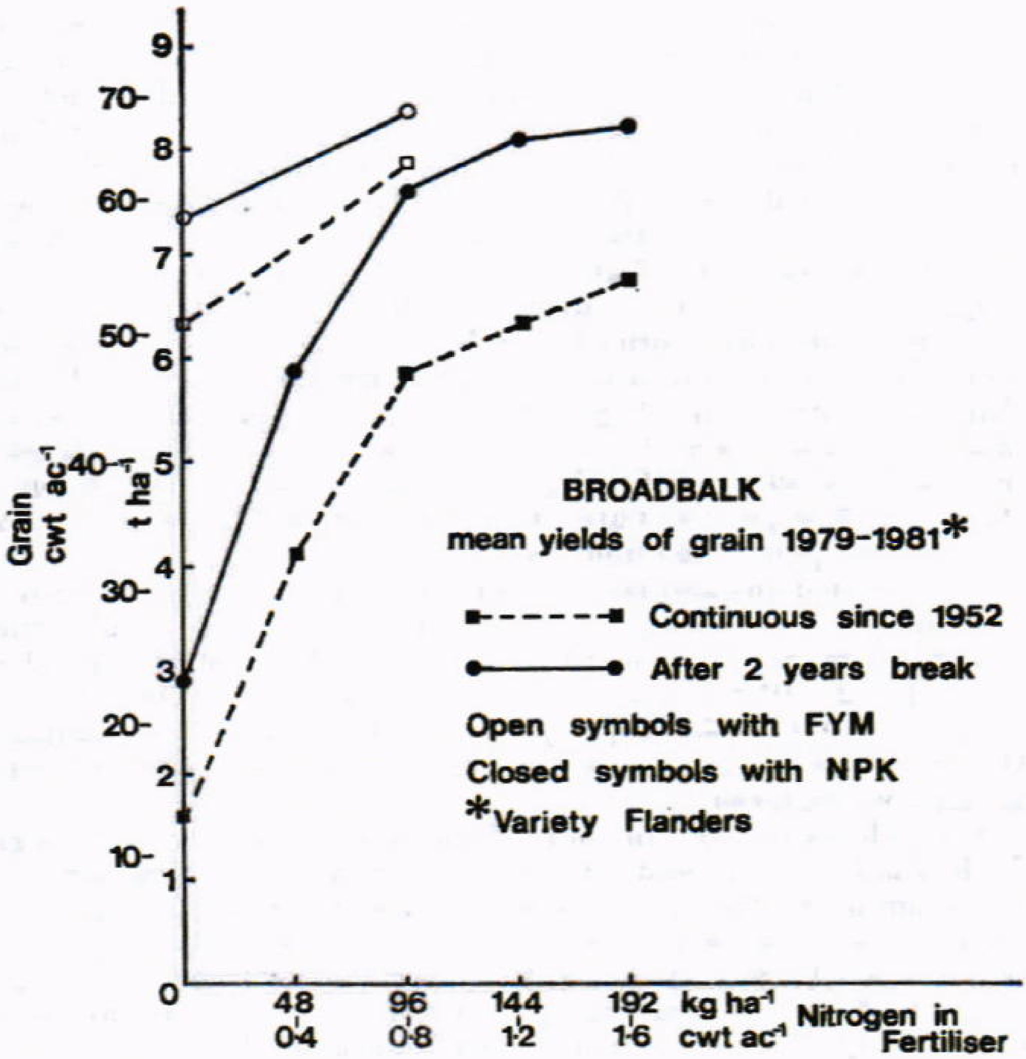


Additional information on Broakbalk yields. See page 53

P.T.O

ROTHAMSTED EXPERIMENTAL STATION GUIDE

Additional Information—April 1982

Entomology Department

Page 12. PROTEIN PRODUCTION FROM WASTE USING EARTHWORMS

High quality protein for feeding livestock is expensive and imports currently cost over £200M per annum.

The disposal of organic and human wastes raises ever-increasing problems as the intensity of animal rearing increases, as urban populations expand and as environmental restrictions on disposal multiply.

Research organised from Entomology Department, with help from the Biochemistry Soils and Plant Nutrition and Soil Microbiology Departments and Chemical Liaison Unit, has demonstrated that high quality feed protein, in the form of earthworms, can be produced from organic wastes which are converted into useful soil additives.

Early work showed that earthworm activity promotes root growth, particularly of direct drilled cereals. Investigations into breeding earthworms for inoculating soils with poor natural populations showed that worms are outstandingly efficient at converting organic waste into protein containing all essential components for a balanced supplement to livestock feed. Feeding trials have shown that earthworms are an excellent protein source for fish farming and there is evidence that pigs and poultry can utilize it equally well.

The potential financial benefits to the economy are impressive. Over 100 million tons of cattle, pig and poultry waste, and 30 million tons of human sewage are produced annually in the UK and its disposal is costly. If only 10% of it were exploited for earthworm culturing, feed protein worth £300–400M per year could be produced. In addition, land wastage and dumping would decrease, and less tangible environmental costs be saved.

Research has solved many of the basic biological problems although work continues on waste processing for maximum productivity, development of efficient earthworm strains, livestock feeding trials, and utilization of worm protein. There is enormous scope for commercial exploitation. Further management expertise and capital is being sought to develop the technology suitable for either on-farm livestock units, or large-scale production of worm protein meal.

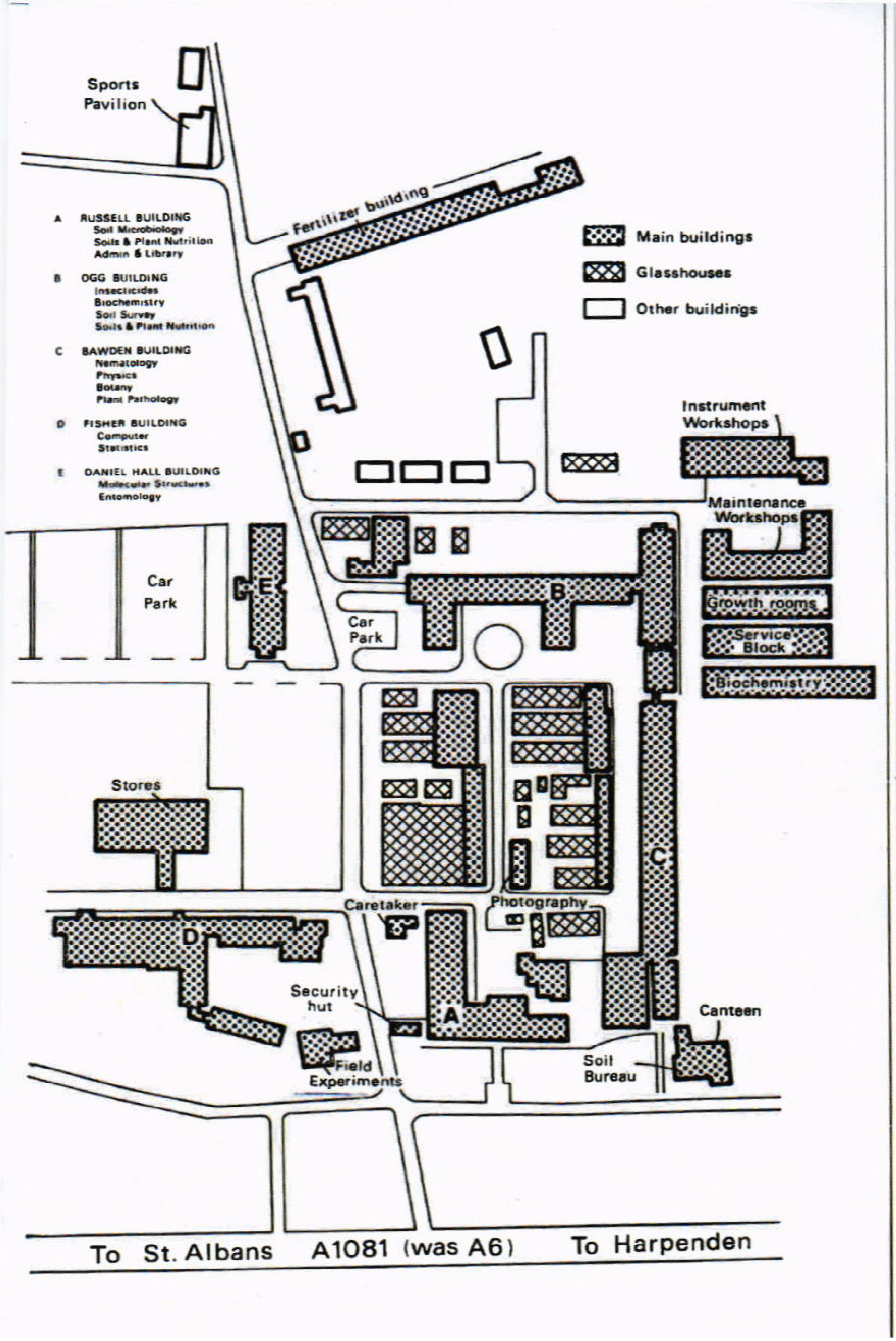
This long-term fundamental research on earthworm biology has demonstrated how such work can provide a basis for rapid commercial exploitation when economic and environmental circumstances become appropriate.

Insecticides and Fungicides Department

Page 17, line 12. Structural requirements for selectivity to pests over beneficial predators and parasites are being investigated.

Page 18, line 10. A successful recent design of electrostatically charged droplet applicator is being investigated in field trials and commercial exploitation through patents assigned to BTG/NRDC is expected to follow.

P.T.O.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D
Security hut
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Field Experiments
Soil Bureau
Canteen
To St. Albans A1081 (was A6) To Harpenden