ROTHAMSTED RESEARCH

Rothamsted Experimental Station Report for 1986

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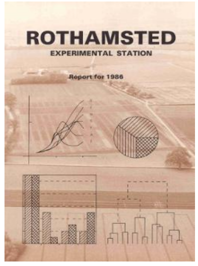

Soils Division

A. E. Johnston

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INTRODUCTION

The award of a MAFF Open Contract to measure nitrate losses under a range of arable crops highlights a growing awareness of the relationship between agriculture and the environment. Data on the amounts of nitrate at risk to leaching during winter are urgently needed because some of this nitrate may eventually appear in potable waters. There is concern that concentrations may increase above current legal limits in areas where, as yet, there is no problem and without reliable data it is not possible to predict likely increases over the next few years. Such predictions also require good estimates of the probable increase in nitrogen fertilizer use and N offtakes in crops. Survey of Fertilizer Practice data suggest that the rate of increase in fertilizer N use is now less than envisaged some years ago whilst the larger crops grown now remove more N. Our recent work has identified agronomic practices which help decrease the amount of nitrate at risk to leaching in autumn. These include ploughing in of straw, early drilling of autumn-sown crops and not applying N in autumn, late winter and early spring. Soil cultivation and the presence or absence of land drains also affect the amounts and rates of loss of nitrate. Although drainage from heavy land usually discharges into surface drains the nitrate content of such water is important if it has to be used to blend with that from deep aquifers. Recent soil analyses suggest that there is little mineral N remaining in soil immediately after harvest and the nitrate which accumulates in autumn comes from the mineralization of organic matter. It is this process which needs to be understood and, if possible, controlled. One of the dangers of fallowing land for a year, if 'set aside' is adopted as a policy for limiting cereal production, will be that mineralization of organic matter during the spring and summer will only increase the amount of nitrate at risk to leaching.

Not only does agriculture have an impact on the environment but man's activities adversely affect agriculture. There are acidifying inputs to soil from the atmosphere which have to be corrected by liming, at a cost to the farmer. In a wider environmental context, recent work shows that land under deciduous woodland acidifies more rapidly than that under grassland. Thus any large-scale afforestation of lowlands could possibly give rise not only to acid soils but also to acid leachates with aluminium concentrations sufficiently large to affect aquatic ecosystems. Currently sulphur deposition supplies most of the sulphur input to our soils and if this source were removed regular sulphur applications would be needed to agricultural soils. Our data on wet and some dry deposition from Broom's Barn and Woburn are now fed into the UK Precipitation Composition Monitoring Network.

Disposal of metal-contaminated sewage sludge to land can affect many microbiological processes. Legumes grown on such soils are often nitrogen-deficient, the many small white nodules on the roots being very inefficient nitrogen fixers. Nitrogen fixation by free living organisms also appears to be affected. We report so far unrecognized and unidentified inputs of 30 to 40 kg N ha^{-1} in one experiment. Inputs of such magnitude are important, especially on non-agricultural soils. Any decrease in the amount of biomass diminishes the turnover of nutrients which are essential for plant nutrition.

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Work on straw disposal shows how difficult it is to control cereal volunteers when cereals are grown continuously if only shallow cultivation is used for incorporation. Recent studies suggest that the cause of possible adverse effects of straw on crop growth is competition for nitrogen between plants and straw-decomposing microbes, rather than toxins. In most cases oxygen demand for straw decomposition is unlikely to exceed supply.

Studies on suitable crops to replace cereals continue. There is a much expanded programme on oilseed rape; amounts and times of applying N tested in one experiment showed that the increased yield of seed from extra nitrogen was more than offset by a lower oil content so that oil yield was lessened by increasing N. Ploughing and conventional seedbed cultivation seriously delayed drilling and many of the small plants from the late sowing failed to survive the winter. However, spring growth, like that of winter wheat, appreciably compensated for the smaller number of plants which survived.

If legumes are to play a greater part in farming systems of the future, then our continuing work at the fundamental and practical level is justified. We hope to elucidate the genetic factors affecting the efficiency of nitrogen fixation in *Rhizobium* because many naturally occurring species are very inefficient nitrogen fixers and genetic manipulation offers a way of improvement. However, the general unease about releasing genetically-altered material has led to the start of an assessment of the likely risks. This work is closely linked to that on factors controlling survival of microorganisms in soil. At the practical level the reported adverse effect of increasing pH on lupins highlights the need to question current recommendations about the most suitable pH for growing them. Improvements in inoculant technology should make it possible to develop cheap, effective inoculation techniques to increase yields of legumes sown in soils which may not have grown them for many years. Work on dual inoculation with *Rhizobium* and vesicular-arbuscular mycorrhizal (VAM) fungi to improve the growth of clover in hill pastures has been completed. Similar technology is proving very successful in increasing yields on acid, infertile soils in Colombia.

For the first time, trehalose and another unidentified carbohydrate have been detected in spores of *Glomus* species. This together with advances in the biochemical characterization of VAM fungi, is improving fungus identification and our understanding of host–fungi relationships. Bacteria isolated from the rhizosphere are being tested as biocontrol agents for take-all and although they do not appear to affect the take-all fungus they do increase biomass of wheat roots. Other organisms are being examined as producers of potentially useful secondary metabolites.

Studies on plant nutrition have continued. At the cellular level the effects of anions on pyrophosphate-dependent proton transport in vesicles of tonoplast has highlighted problems with currently available techniques and these are being resolved. At the whole plant level nutrient fluxes into wheat roots grown in solution culture showed that after depriving plants of N for five days there was no subsequent compensatory growth when N supply was restored.

Spring-sown crops are likely to be affected more by soil structure and tillage than those sown in autumn. Therefore any move away from autumn-sown crops makes studies on soil structure more relevant. At the detailed level forces between individual particles have been related qualitatively to the shear modulus of pastes of the clay fraction. The shear modulus decreased with increasing proportions of dithionite extractable iron and therefore dithionite extractable iron content and the goethite to hematite ratios have been determined for a number of soils. Cracking of drying clay bars has been shown to depend on type of clay and not on initial water content. The advantages of preparing seedbeds in autumn for sowing crops in spring has been related to the cloddiness of the seedbed which affected emergence through its effect on the mechanical strength of the surface soil. Patterns of fissures in soil have been determined using spatial analysis. The ratio of red to near-red reflectance was shown to be the best yield predictor for cereals using remote sensing techniques.

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Finally, and with regret, we report the continued loss of posts as core funding continues to decline. In the general area of soils and plant nutrition it is proving very difficult to get industry support for our work although levy funding through the Home Grown Cereals Authority is a step in the right direction. The decision to transfer work on nitrogen fixation to the Welsh Plant Breeding Station was taken and two staff and two posts transferred. This was a major loss but otherwise it has proved possible to maintain some staff on each of the major topics on which we work. How long this can continue if the agricultural and supporting industries are unable or unwilling to give direct support remains to be seen.

SOIL MICROBIOLOGY

General soil microbiology

Rhizosphere pseudomonads. Over 1800 isolates of *Pseudomonas* spp. have been obtained using a novel selective medium from rhizosphere soil and roots of wheat showing take-all decline, onions and a variety of non-agricultural plants. The bacteria are being tested as biocontrol agents for take-all; the importance of the source of the bacteria, as well as problems of reproducibility and the mechanism of interaction with infected wheat, are being examined. Some bacteria which greatly increase the biomass of wheat roots without greatly affecting the take-all fungus have been detected in initial tests. The interaction of the same collection of bacteria with white-rot of onions will be investigated in collaboration with Dr. A. Entwistle, Institute for Horticultural Research, Wellesbourne. (Macdonald)

Soil actinomycetes. Actinomycetes which belong to genera other than the well exploited *Streptomyces* are being isolated from a wide variety of soils. The best sources and means of isolating producers of potentially useful secondary metabolites are being identified with the object of supplying the pharmaceutical industry with novel bacteria. (Macdonald and McLeod)

Microbial processes in straw decomposition. Although there are many reports on rates of straw decomposition in the field there is little information on the identity of the microbial populations involved. Recent assessments suggest that fungal species, particularly *Chaetomium, Fusarium* and *Trichoderma,* are the initial agents of decay and these may subsequently be replaced by basidiomycetes. It is not yet clear whether microbial populations differ significantly between soil types nor whether differences in populations can influence either decay rate or the production of phytotoxins. However, studies using pure and simple mixed cultures are examining the ability of these organisms to attack lignin and phenolic acids which protect cellulose and hemicelluloses in cell walls from attack by cellulases. If suitable fungi can be identified they will be evaluated as potential microbial inoculants to accelerate the rate of straw decay. (Harper and Bowen)

Vesicular-arbuscular mycorrhiza (VAM) fungi

Investigation of transfer of opines from plant host to VA mycorrhizal fungus. The exact nature of the compounds transferred between mycorrhizal fungi and their plant hosts is unknown but is important both in understanding the symbiosis and also in any future genetic manipulation of the fungi to enable them to synthesize novel compounds and transfer them to plants.

A group of unusual compounds, opines, have been found in plants transformed with oncogenic agrobacteria and are potential marker molecules because most organisms cannot

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catabolize them. Attempts to transfer opines abundant in potato plants transformed by *Agrobacterium rhizogenes* to a fungal symbiont were made using transformed and untransformed plants infected with the VAM fungus *Glomus mosseae* in pot culture. After 20 weeks extracts of roots and fungal sporocarps free from any plant material were assayed for opines using paper electrophoresis and silver nitrate staining (Petit *et al.*, *Molecular and General Genetics* (1983) **190,** 204–214). No trace of mannopine or mannopinic acid (the most abundant opines in the transformed host), or of agropine, was detected in extracts from 10 mg sporocarps although both were clearly present in extracts from transformed root. However, an uncharged silver nitrate-staining compound, probably trehalose (see report by Amijee and Stribley) was detected in sporocarp extracts from transformed and untransformed roots.

Failure to detect mannopine in sporocarps indicates either that it was not transferred across the plant-fungus interface, or the fungus could catabolize it, or it does not accumulate in spores and the amount present was too small to detect. The first and last of these options are most probable; further experiments will be made to elucidate the matter. (Hirsch and Spokes; Gibson, with Ooms, Biochemistry)

Comparison of strains. The infective propagules of two isolates of *Glomus tenuis* (fine endophyte) were investigated using inocula obtained from a pure culture of *G. tenuis,* originally isolated from Sawyers field at Rothamsted, and a mixed culture of *G. tenuis* and *Acaulospora laevis,* originally from New Zealand. Each inoculum was fractionated using sieves of six mesh sizes ranging from 250 to 10 μm and the size fractions were then tested on *Trifolium repens,* grown in Sawyers soil, and *Allium porrum,* grown in Woburn soil. Microscopic examination of roots of *A. porrum* revealed that neither isolate had spread although there were abortive entry points and patches of external hyphae on the root surface. Material from the 30 μm fraction of both original inocula showed the highest infectivity in *T. repens* resulting in a consistent effect on plant growth. The infection formed by the New Zealand inoculum was of the fine endophyte only. The feasibility of adopting this method for the isolation of fine endophyte species from soil is being investigated. (Sainz, Grace and Hayman)

Biochemical characterization of fungi. Isozyme variation within *Glomus* spp., using isolates from different sites, showed that *G. mosseae* is a heterogeneous species which could include *G. monosporum*. *Glomus clarum* was easily distinguished from *G. caledonium* and *G. mosseae* but not from *G. manihotis*. Isozyme analysis on extracts of external mycelium or infected roots has been used to characterize fungi which are difficult to identify because they are non-sporulating or because their spores lack distinctive morphological features. (Hepper; Azcon-Aguilar, Grace, Rosendahl and Sen)

Fungal competition. The extent of leek root colonization by pairs of fungi when one was placed below the seed and the other dispersed in the soil was influenced both by fungal species and placement. *Glomus fasciculatum* was not competitive and failed to infect roots in the presence of *G. caledonium* or *G. mosseae*. With the latter two fungi, the one dispersed in the soil predominated in the root. (Hepper; Azcon-Aguilar, Rosendahl and Sen)

Susceptibility of roots to infection. Roots of leek (*Allium porrum*) and clover (*Trifolium repens*) which were challenged with inoculum of *G. mosseae* along their entire length did not become uniformly infected. Subapical regions were most heavily colonized and there was a sharp basipetal decline in susceptibility to infection, particularly in clover. This 'window of opportunity' was considerably narrowed in roots of both leeks and clover by high concentrations of soil phosphate. (Amijee and Stribley)

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Host-endophyte relationships

Spread of infection. A detailed study of effects of phosphorus (P) in soil on spread of infection in leek roots (*A. porrum*) from a layer of inoculum of *G. mosseae* (*Rothamsted Report for 1985*, 160) has continued. The length of infected root decreased markedly when bicarbonate-soluble P exceeded 140 mg kg^{-1} because of the combined effects of an increase in the time taken for initial infection, and a sharp decline in the rate of spread of infection along the cortex of both adventitious and lateral roots. High concentrations of soil P also appreciably diminished the fungal biomass per unit length of mycorrhiza. Although rates of spread of infection along the cortex were the same for all treatments they were always greater in laterals than in main axes. These features of spread of infection, together with observations on effects of P on root growth, are being incorporated into a simulation model. (Amijee and Stribley)

Fungal carbohydrates. For the first time trehalose has been detected in spores of *Glomus* spp., using gas-liquid chromatography of ethanol extracts. Another unidentified carbohydrate, possibly a disaccharide, was the principal component of ethanol extracts of extra-radical mycelium. These carbohydrates, unique to the fungus, are potentially valuable for studies on transfer of carbon from host to fungus in the mycorrhizal symbiosis. (Amijee and Stribley)

Invertase in roots. The activity of invertase in mycorrhizal roots of leek plants was twice that of roots of uninfected controls growing at a similar rate. Gel electrophoresis showed that the activity of host enzymes had been stimulated and that the contribution of fungal invertase was small. This work shows that mycorrhizal infection can have effects on the host not explicable by enhanced P nutrition. (Snellgrove, Stribley and Hepper)

Nitrogen fixation

Genetic factors affecting the efficiency of nitrogen fixation. The genetic location of factors controlling efficiency of symbiotic nitrogen fixation has implicated both the symbiotic (Sym) plasmid and the genomic background (*Rothamsted Report for 1985*, 161). Significant differences in shoot dry weight and nitrogen content have been obtained in peas inoculated with *Rhizobium leguminosarum* strains carrying different symbiotic plasmids in the same genomic background, the Sym plasmid appearing to affect the carbon cost and electron allocation to nitrogenase (which was inversely correlated with plant dry weight). However, the time and pattern of onset of nitrogenase activity in pea root nodules was determined by the *Rhizobium* genomic background which comprises of other plasmids and the chromosome. Two *R. leguminosarum* isolates differing in these parameters are being investigated further to identify the location of symbiotically important genes not carried on the Sym plasmid. Chromosomal hybrids between the two strains have been constructed and are being tested on plants to ascertain whether such genes map to the chromosome rather than other plasmids. (Witty and Hirsch; Gibson, with Dr. L. Skøt, Risø National Laboratory, Denmark)

A new class of symbiotic genes in *Rhizobium*. Although fast growing rhizobia may contain many large plasmids it has been thought that all the genes required for initiation of nodule formation on leguminous plants, and for symbiotic nitrogen fixation, were clustered together in one region of one of the plasmids, the Sym plasmid. Recently, however, it has been shown that genes essential for nitrogen fixation are outside this main cluster in *Rhizobium meliloti* (Batut *et al.*, Molecular and General Genetics (1985) **199,** 232–239).

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DNA probes containing these genes were hybridized to gel blots of plasmid DNA from a range of different *Rhizobium* species that carried from two to six plasmids, the Sym plasmid having been identified in each case by its homology to a DNA probe containing the structural genes for nitrogenase. In some strains the Sym plasmid showed strong homology to one of the *R. meliloti* DNA probes but in other strains non-Sym plasmids showed weak homology. This implies that genes related to the *R. meliloti fix* genes are present on non-Sym plasmids and the possibility that they are functionally homologous (i.e. that they can complement the *R. meliloti* mutants) and that they are essential for symbiotic nitrogen fixation, is being investigated. (Hirsch and Snellgrove; Gibson and Latham, with Dr J. Batut, INRA, Toulouse)

Assessing gene transfer from genetically-marked *Rhizobium* in the soil. One of the risks in releasing genetically manipulated soil microorganisms is that they may exchange genetic material with indigenous strains producing hybrids with novel and perhaps unwanted properties. The probability of this occurring is difficult to assess because little information is available on gene transfer in the soil microflora. To determine the risk, a strain of *Rhizobium leguminosarum* carrying two antibiotic resistance markers on the chromosome and a transposon, Tn*5*, determining antibiotic resistance on a transferable symbiotic plasmid, has been constructed. The frequency of transfer of the Tn*5* marker to other rhizobia and different bacterial genera is being determined in the laboratory. If permission is granted by the Advisory Committee on Genetic Manipulation of the Health and Safety Executive this marked strain will be released in the field, as a pea inoculant, to monitor the spread of the Tn*5* marker to native rhizobia and other soil microorganisms. (Spokes, Hirsch and Day; Gibson and Latham)

Measurement of nitrogen fixation using ^{15}N. Methods have been developed to measure nitrogen fixation in tropical grain legumes and the rhizospheres of tropical cereal crops using the isotope dilution method. Estimates of fixation are based on the difference in ^{15}N enrichment between the fixing crop and a non-fixing reference plant when both have access to the same labelled pool of combined N in soil. The most accurate technique involved incorporating ^{15}N-fertilizers into soil in slow-release forms, preferably with a carbon source to promote microbial growth. Mineralization of the ^{15}N-labelled organic matter provided the labelled source of combined nitrogen. Work with *Phaseolus* genotypes in Colombia has shown considerable variation between seasons and locations in amounts of N_2-fixed. The contribution of N_2-fixation to total crop nitrogen ranged from 10–15%, i.e. fixation between 5 and 45 kg N ha^{-1}.

Repeated attempts to measure N_2-fixation associated with sorghum and millet roots in glasshouse experiments at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have failed to demonstrate significant fixation despite manipulation of the experimental conditions to favour it. We conclude that it is unlikely that sufficient N_2-fixation occurs in the rhizosphere of these species to be worth commercial exploitation. This project, which is now completed, was funded by the Overseas Development Administration (ODA) and carried out in collaboration with the Centro Internacional de Agricultura Tropical (CIAT) and ICRISAT. (Giller, Day, Witty and Edwards; Smith)

Crop inoculation

Mycorrhiza in tropical America. A collaborative project with CIAT in Colombia is being funded by EEC to study interactions between rock phosphate fertilizer, *Rhizobium* and VA mycorrhiza and the growth of forage legumes in acid infertile soils. *Rhizobium* bacteria were selected for effective nodulation on different tropical legumes, and suitable VAM fungi were

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isolated from Colombian Llanos soil and established in pot cultures at Rothamsted. The effects of, and interactions between, the selected rhizobia and mycorrhizal fungi are being studied at Rothamsted. Complementary field experiments have been started at Carimagua Experimental Station in the eastern plains of Colombia. *G. manihotis* and *Entrophospora colombiana* were selected as efficient VAM fungi for field inoculation and are being compared with the native population in relation to crop growth and yields, population dynamics and to determine how inoculum densities might affect subsequent crops. Inoculation has been very beneficial, increasing both root infection and crop growth, especially in the presence of rock phosphate. The results show great potential for inoculation in these impoverished soils, particularly if rock phosphate is applied also. (Arias, Dodd, Hayman and Koomen)

Mycorrhiza, *Rhizobium* and white clover in upland grasslands. These experiments, begun in 1983 and 1984 (*Rothamsted Report for 1983,* 167, and *for 1984,* 175), terminated in 1986. Yields were higher in 1986 than in the two previous years, mainly because of better weather conditions for growth of clover. The herbage on both mineral and peaty soil in mid-Wales was harvested in late July. Both total herbage and clover responded to added P (90 kg P ha^{-1} as superphosphate) in both the 1983 and 1984 sowings. The VA mycorrhizal inoculants significantly increased clover yields even in the presence of P on both soils. Clover dry matter yields (kg ha^{-1}) from the 1983 sowings on the mineral soil were 1155 with both P and VAM fungi, 657 with P alone, and 100 from the controls. Corresponding yields for 1983 sowings on peat were 327, 209 and 77 kg ha^{-1}, respectively.

These results agree with earlier findings (*Rothamsted Report for 1982,* 215 and *for 1980,* 202) and confirm the benefits of mycorrhizal inoculation in the presence of standard dressings of superphosphate for clover grown on very P deficient soils. (Hayman, Day, Dye and Grace)

Effects of pH on lupins. For many microbiological investigations it is necessary to grow plants in soil-free culture in order to exclude indigenous *Rhizobium* strains; most grain legumes grow satisfactorily on such standard nutrient solutions. Lupins, however, often show quite acute nutritional disorder when the pH of the solution is close to 7 but these symptoms disappear if the pH is reduced to 5·5 or less. Lupins will tolerate higher pH levels when grown in soil because of its better buffering capacity.

Recommendations for growing lupins suggest that soils of pH 6·4 or above should be used with no mention of any upper pH limit related to possible nutritional complications at high pH. The effect of soil pH on the growth, nodulation and nitrogen content of *L. albus,* was determined by growing them in pots containing equal parts of loam and peat, the pH of which was amended with $Ca(OH)_2$ or sulphur to span the range 4·6 to 8·2. Three cultivars of *L. albus,* Kalina, Lublanc and Vladimir, were grown and for each there was little difference in growth, nodulation and N content from pH 4·6 to 6·5. However as pH increased to 8·2 there was progressively poorer growth and plants showed acute chlorosis above pH 7·5. It appears that lupins are well adapted to acid soils and should not be recommended for alkaline soils until the reasons for the observed chlorosis are better understood. (Day and Chandler)

Methods of inoculation. Although the benefits of microbial inoculation with efficacious organisms, such as *Rhizobium* are proven experimentally the procedure is often unpopular with farmers. This is particularly true when slurry inoculation techniques are used with large seeded legumes drilled at high seed rates. An adhesive has now been identified which leads to a two- to three-fold increase in retention when the inoculant is applied by dry dusting. It has no adverse effects on rhizobial numbers or inoculant shelf life, and can be added to the

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carrier material during production. It also improves adhesion when the inoculant is applied to moist seed. With the new formulation the longevity of *Rhizobium* on the seed surface is equivalent to that achieved when gum-arabic slurry inoculation is used. Such is the commercial potential of this new formulation that the Agricultural Genetics Company (AGC) filed a patent application and all the New Plant Products Laboratories (NPPL) inoculum for lupin, soya bean and *Phaseolus* during 1987 will use it. (Williams and Day)

Granular inoculants. Most *Phaseolus* and lupin seed sown in the UK is dressed with fungicides that are toxic to *Rhizobium* making normal 'slurry' inoculation ineffective in most situations. Granular inoculants were suggested as alternatives to the 'slurry' method. They were intended to be either combine-drilled with the seed or broadcast pre-sowing (*Rothamsted Report for 1983,* 169). However, the granules available then were commercially unacceptable because of their short shelf-life and high cost of production. Cheap granular formulations have now been developed which still contain more than 10^9 rhizobia per gram four months after production. They will shortly be available through NPPL. (Williams and Day)

Staff and visiting workers

A. E. Johnston was appointed Acting Head of Department on 10 February 1986. Ingrid Arias and J. C. Dodd arrived in January for 18 months; they will work on the collection and monitoring of results in field work in Colombia; Jane C. McLeod came in August to work with R. M. Macdonald for one year. K. E. Giller left in September to take up a new appointment at Wye College, University of London, P. Edwards' appointment terminated in August, Muriel Chandler left in March and Robin Sen in April. J. F. Witty and M. Dye both transferred to Welsh Plant Breeding Station in August. J. Spokes and R. C. Snellgrove were transferred to EEC-funded projects.

K. E. Giller spent three months working at CIAT and three weeks at ICRISAT and visited nitrogen fixation research laboratories in Brazil. D. S. Hayman visited CIAT, Colombia, along with J. C. Dodd, Ingrid Arias and Irene Koomen in connection with the EEC-funded collaborative projects between CIAT and Rothamsted. Penny R. Hirsch participated in a discussion meeting on *Vicia faba* at the University of Göttingen, FRG, and went with R. C. Snellgrove to Toulouse, to discuss progress of the project funded by EEC on 'late symbiotic genes in *Rhizobium* and construction of improved strains'. D. S. Hayman attended a scientific advisers' meeting on mycorrhiza at the International Foundation for Science, Stockholm, and was invited to Brazil to lecture at the First Brazilian Symposium on Biotechnology and to participate in meetings at Brazilian universities and research institutes. Christine M. Hepper visited INRA research institutes at Nancy and Dijon for discussions on collaborative work. F. Amijee presented a poster display at the 13th International Congress of Soil Science in Hamburg. J. M. Day lectured in India and Philippines and visited France and Italy for discussions regarding the production and use of inoculants for legumes. R. M. Macdonald attended the 4th International Congress on Microbial Ecology in Ljubljana, Yugoslavia.

F. Amijee was awarded a Ph.D. by the University of Leeds. Concepción Azcon-Aguilar returned home to Granada, Spain in October, Maria J. Sainz returned to Santiago de Compostela, Spain in August and S. Rosendahl returned to Copenhagen, in December, all having spent six to 11 months in the Department. M. Honrubia returned to Murcia, Spain having worked on mycorrhizas for three months in the Department.

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SOILS AND PLANT NUTRITION DEPARTMENT

Causes of yield variation

Comparison between previous crops. Previous cropping has been shown to be a major cause of yield variation in winter wheat through its effect on soil-borne pathogens and residual nitrogen. In 1985 benefits of residual N on early growth at Rothamsted were nullified by lodging caused by summer storms, in 1986 more residual N after rape than after oats had no effect at Rothamsted but at Saxmundham previous beans rather than wheat improved yield in both years.

Wheat following rape or oats at Rothamsted. The effects of soil and fertilizer N on tillering, growth and yield of winter wheat, cv. Avalon were measured (see p. 31). Five factors at two levels were tested in all combinations: (1) previous crop, spring oilseed rape vs. spring oats; (2) sowing date, 20 September vs. 18 October; (3) winter N, O vs. 50 kg ha^{-1}; (4) spring N as a single 200 kg ha^{-1} application vs. four 50 kg ha^{-1} applications; (5) summer N, O vs. 50 kg ha^{-1}. The amount of winter N was equal to the measured difference in soil NO_3-N to 90 cm after rape and after oats. Winter N was applied as urea on 27 November, spring N as 'Nitro-Chalk' on 25 April (single application) and on 6 March, 1 April, 21 April, 19 May (divided application); summer N, also as 'Nitro-Chalk', was applied on 9 June. Additionally, factors 1, 3, 4 and 5 were tested in combination on early-sown wheat, but with the spring and summer N applied later than normally recommended (single spring application on 19 May, divided on 1 April, 21 April, 19 May and 9 June; summer N on 25 June).

Yields of grain with September and October sowing were 9·41 and 8·94 t ha^{-1} respectively after rape, 9·49 and 8·99 t ha^{-1} after oats. Thus, although the early-sown wheat yielded significantly more than later-sown, yields were no larger with the extra 50 kg ha^{-1} of residual soil NO_3-N provided by the rape. Poor growth in autumn 1985 may have prevented the expected improvement. There were no other significant effects on grain yield. Withholding the spring N from the early-sown until later than normally recommended had no effect on yield when it was divided and decreased yield by only 0·2 t ha^{-1} when applied as a single dressing. (Penny and Darby with Thorne, Physiology and Environmental Physics; Prew, Field Experiments and Todd, Statistics)

Wheat following beans or wheat at Saxmundham. A bread-making wheat (Moulin) and a feeding wheat (Galahad) were grown without or with 60 kg N ha^{-1} (urea) applied on 25 March and with a range of N dressings ('Nitro-Chalk') applied on 23 April, after winter beans and after winter wheat. A combined aphicide and fungicides programme was also tested.

On 12 November 1985 amounts of NO_3-N in the soil to 90 cm depth were 106 and 51 kg N ha^{-1} after beans and wheat respectively; 50 kg ha^{-1} of fertilizer N had been applied to the seedbed on 8 October. Grain yields (t ha^{-1}), of both cultivars were larger after beans than after wheat and larger from Galahad than from Moulin; after beans, Galahad 9·11, Moulin 8·92; after wheat, Galahad 7·27, Moulin 6·85. N applied in March increased yields of wheat after wheat at all levels of April-applied N (average increase 1·20 t ha^{-1}) but not with more than 100 kg N ha^{-1} after beans (average increase 0·36 t). Yields increased with each increment of N applied in April. The aphicide and fungicide programme increased mean yield by 0·5 t ha^{-1}. The largest yield of Galahad (10·24 t) and of Moulin (10·04 t) were both obtained when grown after beans and given 190 kg N ha^{-1} in April and the aphicide and fungicide programme. (Penny, Widdowson, Darby and Hewitt)

Factors limiting the yield of winter barley. This experiment completed the series. Following the dry autumn in 1985, many volunteer plants emerged after the barley was sown which

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increased the plant population to 480 m^{-2}, approximately 50% more than that for the previous two years. Despite the large maximum number of shoots from these additional plants the number of ear-bearing stems stabilized at 1070 m^{-2} by 2 June, similar to previous years. Grain yield was smaller than in 1985, possibly because of the many tillers which failed to form ears. Only treatments which controlled diseases significantly affected yield which was increased from 5·80 to 6·08 t ha^{-1} by 'Baytan' seed treatment and from 5·51 to 6·37 t ha^{-1} by spring and summer disease control. (Darby)

Factors affecting the yield of winter oilseed rape. A multifactorial experiment tested the same factors (see p. 26) as in the previous year. Growth, nitrogen uptake and the incidence of pests and diseases were assessed throughout the year and yield was measured at harvest.

The autumn of 1985 was very dry which delayed the emergence of the late-sown crop. This in turn delayed the application of a post-emergence herbicide which caused severe competition from volunteer cereals. The plant population on 3 December was 120 and 52 plants m^{-2} for the early and late-sown crops respectively, and on both crops a further 10 plants m^{-2} were lost over winter.

Unlike 1985, when shedding losses were large, yields from combine-harvested and hand-harvested areas taken nine days earlier were similar. The mean combine-harvested yield was 3·72 t ha^{-1}, and, in spite of large differences in plant population, the late-sown crop outyielded the early-sown although not significantly. Nitrogen and summer fungicide both significantly improved yields; going from 175 to 275 kg N ha^{-1} increased yields from 3·61 to 3·83 t ha^{-1} whilst applying fungicides increased yield from 3·63 to 3·81 t ha^{-1}. In combination these treatments were additive, yielding 3·93 t ha^{-1}. The oil content of the seed was little affected by sowing date but increasing fertilizer N depressed it significantly, from 49·9 to 49·0% oil in dry matter. The extra yield from the larger amount of N was sufficient to offset the lower oil content; oil yields were 1623 *v.* 1691 kg ha^{-1}, with 175 and 275 kg N ha^{-1} respectively. (Darby)

Recovery of deep N by wheat. In 1985 wheat recovered mineral N from its maximum rooting depth of 160–180 cm (*Rothamsted Report for 1985*, 165). Thus any soil- or fertilizer-derived N leached below 180 cm could eventually find its way into the ground water and become a potential pollutant. Because of the importance of this observation, ammonium nitrate fertilizer was applied in autumn 1985 and spring 1986 and its fate followed by crop and deep soil sampling to determine how far it was leached and how effectively the deep N was recovered.

Wheat, cv. Avalon, was sown in late September. In December the crop contained 35 kg N ha^{-1} and the soil, down to a depth of 180 cm, contained 146 kg ha^{-1} of KCl-extractable NH_4- and NO_3-N, 53 kg between 0 and 30 cm and 28 kg below 90 cm. The crop was top-dressed in December with NH_4NO_3 solution which added 96 kg N ha^{-1}. In March the soil contained 137 kg N ha^{-1}, 34 below 90 cm. A further top-dressing of NH_4NO_3 fertilizer in April added an extra 116 kg N ha^{-1} so that, when sampled in May, the soil below 90 cm had its largest N content, 46 kg N ha^{-1}. At the final sampling in July, this had decreased to 11 kg. Over the period May to July there was a net soil moisture deficit with, therefore, little or no through drainage. Thus, mineral N leached from the top 30 cm of the soil was taken up by the crop, down to a depth of at least 150 cm and possibly to 180 cm; the deep N below 90 cm was taken up between May and July. (Weir and Barraclough; Green and Kent)

Efficient use of applied fertilizer nitrogen

Recovery of foliar-applied urea by winter wheat. The efficiency with which nitrogen fertilizer solutions, applied at about anthesis, can increase percentage protein in grain was

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measured at four sites in 1984. To measure recovery of foliar-applied N, ^{15}N-labelled urea (30 kg N ha^{-1}) was used, half applied before anthesis (Zadoks growth stage 37–39, late May) and half after (Zadoks growth stage 69–73, late June). About 50% of the foliar-applied N was recovered in the crop at harvest. This is rather less than typical values for recovery of ^{15}N-labelled fertilizer applied to soil in April, but a greater proportion of the foliar-applied N was recovered in grain. For crops given sufficient fertilizer N in April to achieve maximum grain yield, late foliar urea at 30 kg N ha^{-1} was as effective in increasing grain protein as an extra 60 kg N ha^{-1} applied to the soil in February, but slightly less effective than an extra 60 kg ha^{-1} soil-applied N in April. The potential of a late foliar application of N to manipulate crop N requires further study, as does the fate of the nitrogen not taken up by the crop. (Powlson, Jenkinson, Poulton, Penny and Hewitt)

Nitrogen balance for the Broadbalk Continuous Wheat Experiment. A nitrogen balance, constructed from the results of experiments with ^{15}N labelled fertilizer over the period 1980–3, shows that there was a substantial input of non-fertilizer N to the crop/soil system. On the plot receiving 144 kg N ha^{-1} yr^{-1}, in which the soil nitrogen content is at equilibrium, the annual offtake of N in grain and straw was 140 kg ha^{-1} and the calculated annual loss of N from both fertilizer and soil was 54 kg ha^{-1}. Because soil N is at equilibrium, the annual N output in crop and losses must be balanced by an annual N input which, in this case, must be 50 kg ha^{-1} and come from non-fertilizer sources. Some of the input is in rain, 10–15 kg N ha^{-1}, and seed, 4 kg ha^{-1}. Other likely sources are from deposition of NH_3, from NO_x and from biological fixation of atmospheric N_2 by photosynthetic cyanobacteria on the soil surface. There is no reason to suspect that this comparatively large input of N, which may well be a conservative estimate, does not occur over large areas of agricultural land in the UK and elsewhere and its magnitude and source should be identified. (Powlson and Jenkinson)

Forms and timing of spring N to oilseed rape. Large single applications of urea in spring tend to scorch oilseed rape, so multiple applications of calcium ammonium nitrate and prilled urea have been compared. Oilseed rape, cv. Mikado, was sown at 8 kg ha^{-1} without seedbed N on 22 August. In spring, none or 200 kg N ha^{-1} was applied either as a single dressing, or divided in six ways spanning four occasions, 12 and 26 March, 24 April and 7 May.

Without N the rape yielded 1·67 t ha^{-1} (90% DM), and with 200 kg N ha^{-1} as either calcium ammonium nitrate or urea yields were 3·99 and 3·84 t ha^{-1} respectively. When applied as calcium ammonium nitrate, N at 150 kg ha^{-1} on 12 March and 50 kg ha^{-1} on 26 March gave the largest yield (4·12 t ha^{-1}). None of the other combinations of calcium ammonium nitrate was significantly worse, except when applied at 100 kg ha^{-1} on 12 March and 24 April.

When applied as urea, N at 100 kg ha^{-1} on 12 March and 26 March gave the largest yield (3·96 t ha^{-1}). No other combination was significantly worse except when all the N was applied on 12 March, or the application was divided between 150 and 50 kg ha^{-1} on 12 and 26 March. Oil content of the rapeseed was unaffected by either form or timing of N. (Darby and Hewitt)

Effect of drainage on the efficiency of nitrogen use. An assessment of the efficiency with which winter wheat growing on the drainage experiment at Brimstone used 130 kg N ha^{-1} was made by ^{15}N balance, by Br^- tracer (to estimate NO_3^- leaching), and directly, by estimating denitrification by acetylene inhibition. Measured losses of N by denitrification, made two or three times a week between N application on 30 April and anthesis at the end of June, were small. On the four main treatments losses (kg N ha^{-1}) were: 3·0 from undrained,

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direct drilled land, 9·1 from undrained, ploughed land, 6·2 from drained, direct drilled land, and 4·2 from drained, ploughed land, i.e. between 2 and 7% of the N applied was lost. About two-thirds of this loss occurred during the second two weeks of May following the onset of wet weather. There was no clear effect of either drainage or cultivation. During the period of measurement, soil temperatures were always above 12°C and soil NO_3-N above 10 μg g^{-1}. Thus, assuming that available carbon was similar on all plots, the factor determining denitrification was soil moisture content. The amounts of N lost by denitrification in 1986 were much less than those reported earlier when spring rainfall was larger (Colburn *et al.*, *Journal of Soil Science* (1984) **35,** 539–547) and further work is undoubtedly justified. (Goulding and C. P. Webster; Rosenani Abu Bakar and Rosemary Weller, Sandwich Student)

Nitrogen prediction system

Practical use. Work on the nitrogen prediction system (*Rothamsted Report for 1985,* 167) has been focused mainly on providing estimates of 'Soil and Crop Nitrogen' for two commercial viewdata systems. The information provided was restricted to farmers growing winter wheat in the Eastern region of England. Current weather data were used to compute the sum of the mineral N in the soil and the N already in the crop. These were compared with estimates based on long-term averages to show whether there was more or less 'Soil and Crop Nitrogen' present than in an 'average' year and by how much. The information was provided for all combinations of crops sown on two different dates, five soil types and three types of precursor croup. This part of the system was also put into a form more easily used by those less familiar with computers. Work on improving the system has also continued and a version incorporating the improved leaching model (*Rothamsted Report for 1985,* 167) is now being tested. (Whitmore and Addiscott; Heys and Bland)

Leaching prediction. From late March to early June estimates of percentage leaching losses of applied fertilizer nitrogen below 25 and 50 cm for the same five soil types were provided for two commercial viewdata systems, to tell farmers about the risk of nitrate loss from seedbed and top dressings of N fertilizer.

Further improvements have been made to the leaching model, particularly in the treatment of evaporation, and a version has been developed for simulating the movement of solutes that are adsorbed by the soil surface. (Addiscott and Bland)

Computer simulation of N-leaching—the rapid immobilization of fertilizer N. The model of Addiscott and Whitmore (*Rothamsted Report for 1985,* 167) was used to simulate mineralization, crop uptake and leaching of soil- and fertilizer derived-mineral N during the period from December to March in the experiment on the recovery of deep N by winter wheat (see p. 49).

By March the model predicted N mineralization from crop residues of 20 kg ha^{-1}, crop uptake of 23 kg N, loss by leaching below 180 cm of 58 kg N, and a total of 184 kg ha^{-1} mineral N, 84 kg below 90 cm. However, the crop, because of winter losses, had taken up only 2 kg N ha^{-1}, and the soil in fact contained only 137 kg ha^{-1} mineral N, 34 kg below 90 cm. If newly mineralized N and crop uptake are ignored there was 47 kg N ha^{-1} not accounted for. This amount could have been lost by leaching below 180 cm in addition to the 58 kg predicted by the model. If however, the N had moved so far down the profile the amount remaining below 90 cm would have been expected to be more and not less than the simulated 84 kg.

A further loss was observed in the period between March and May when the simulation model could not be used. In April after further fertilizer had been added the total of fertilizer

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plus soil mineral N in the profile was 253 kg N ha^{-1}. By May this had fallen to 73 kg whilst crop N had increased by only 53 kg, so that 127 kg N ha^{-1} could not be accounted for.

Between May and June part of the missing N reappeared. An increase in crop N of 90 kg N ha^{-1} was accompanied by a decrease of 47 kg of mineral N in the profile.

Possible explanations of these discrepancies are that NH_4-N added as fertilizer was held in clay minerals, or that part of the total N was immobilized as organic N in the biomass. In either case this N would not be recovered by KCl.

Rapid immobilization of either NH_4- or NO_3-N would buffer added fertilizer N against losses, but this N would need to become available to the crop during the growing season. If such rapid immobilization is confirmed in soils the absence from a simulation model of such a process would lead to over-estimation of the mobility of NO_3 ions and of loss of NO_3-N by leaching. (Weir; Addiscott, Barraclough and Whitmore)

Soil organic matter and biomass

Effects of management on the amount of organic matter in soil. The Rothamsted model for the turnover of organic matter in soil (Jenkinson & Rayner, *Soil Science* (1977) **123,** 289–305; *Rothamsted Report for 1984,* 179) has been further improved. The model now predicts how both total C and biomass C respond to a change in management and also how the pulse of radiocarbon that entered the atmosphere from the thermonuclear bomb tests of the early 1960s influences the radiocarbon age of the soil as measured by radiocarbon dating.

A set of woodland and grassland soil samples collected in 1985 and earlier have now been dated by the Natural Environment Research Council (NERC) Radiocarbon Laboratory. Agreement between modelled and measured values for total C, biomass C and radiocarbon age is encouraging, indicating that the present model can be used to predict how a change in management will influence soil organic matter over the 5–500 year period. (Jenkinson, Parry, Rayner and Vance, with Dr D. D. Harkness, NERC Radiocarbon Laboratory, East Kilbride, and Dr A. F. Harrison, Merlewood Research Station, Grange-over-Sands)

Adenylate energy charge measurements in soil. Our work suggests that in moist soils the soil microbial biomass, although composed mainly of a resting population of microorganisms with a low metabolic rate, maintains a large adenosine triphosphate (ATP) content and high (0·8–0·9) adenylate energy charge (AEC), characteristic of exponentially growing microorganisms *in vitro.* This conclusion is based on ATP measurements on extracts of soil using acidic reagents, e.g. trichloroacetic acid (Brookes, Tate & Jenkinson, *Soil Biology and Biochemistry* (1983) **15,** 9–16). However, other work following extraction with an alkaline $CHCl_3/NaHCO_3$ reagent has shown low (0·3–0·4) AECs in soil, values characteristic of a largely resting soil population (Martens, *Soil Biology and Biochemistry* (1985) **17,** 765–772). Both reagents extract the same amounts of *total* adenine nucleotides from soil, but alkaline reagents do not denature ATPases (Lundin & Thore, *Applied Microbiology* (1975) **30,** 713–721) so that dephosphorylation of ATP occurs during extraction with the alkaline $CHCl_3/NaHCO_3$ reagent and the amount of ATP measured is less than that originally present. We believe that only acidic reagents should be used to measure adenine nucleotides and AEC in soil. (Brookes and Jenkinson; Newcombe)

Biomass carbon measurements in acid soils. In the chloroform fumigation incubation method (Jenkinson & Powlson, *Soil Biology and Biochemistry* (1976) **8,** 209–313), soil biomass carbon is calculated from the CO_2-C evolved by a fumigated soil, less that evolved from a non-fumigated soil as a control. The results generally agree closely with those estimated from ATP or by direct microscopy. However, in very acid soils, pH below 4·5, less CO_2-C is evolved from the fumigated soil than from the non-fumigated control soil, so that

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biomass C cannot be measured. This is probably because non-biomass soil organic matter is not mineralized by the microbial recolonizers in acid fumigated soil, but it is in the nonfumigated control soil during the 0–10 day post-fumigation period. Thus, for soils below about pH 4·2 we suggest that a control is not necessary. When biomasses in strongly acid soils were calculated without a control they agreed closely with those measured by direct microscopy or ATP. Soils at or below pH 4·2 contained very high concentrations of KCl-extractable aluminium. It is possible that this is linked to the reduced activity of microbial recolonizers in acid fumigated soils.

In a new direct method for measuring biomass C, the organic C extracted by 0·5M K_2SO_4 from a fumigated soil, less that extracted from the non-fumigated control soil, has been found to give a direct measure of biomass C. Good correlations betwen results obtained by this new method and by the fumigation-incubation method, modified for use in acid soils as above, have been obtained for soils ranging in pH from 3 to 7·8. Thus direct extraction gives a quick measurement of soil microbial biomass that sidesteps the problem of a suitable control and avoids the ten day incubation period in the fumigation-incubation method. (Vance, Brookes and Jenkinson)

Model for the turnover of organic N in soils. The model which calculates the turnover of organic matter in soils (*Rothamsted Report for 1984,* 179) has been adapted to interact with the model for predicting leaching of NO_3-N (*Rothamsted Report for 1984,* 181). The first model estimates the mineral N in the soil produced by the breakdown of organic matter, and the second the amount which is lost from the system by leaching. Work is now in progress to include the N uptake by the crop for which a model has been developed (*Rothamsted Report for 1984,* 181). The aim is to model the nitrogen cycle for arable crops so that frequent soil sampling is not required to initiate the N prediction system. (Whitmore, Parry and Jenkinson)

Root studies

Soil solution concentrations limiting the supply of N, P, K to maize roots. Maximum N, P, K uptake rates and inflows through roots have been calculated for a 9 t ha^{-1} winter wheat crop grown at Rothamsted (*Rothamsted Report for 1984,* 183). Similar data from Indiana, USA for maize yielding 12 t grain ha^{-1} (Mengel & Barber, *Agronomy Journal* (1974) **66,** 399–402) were used to calculate concentration differences between root surfaces and the bulk soil necessary for diffusive supply, using a simulation model of nutrient transport and uptake (Baldwin *et al.*, *Plant and Soil* (1973) **38,** 621–635). For maize, values of 539 μM N, 56 μM P and 225 μM K (equivalent to 7·7, 1·8 and 9·0 kg ha^{-1} respectively) were obtained which were much greater than those for the high yielding wheat crop. For maize the acutal concentration of N in soil solution, 17 mM, was capable of sustaining the observed inflows by mass flow or diffusion alone. The actual concentration of P, 55 μM, was adequate for diffusive supply. However, for K, the concentration of 212 μM, was not quite adequate for diffusive supply and a small mass flow contribution of about 6% of the total inflow was necessary, and could have been achieved. (Barraclough with Professor S. A. Barber, Purdue University, Indiana, USA)

Root growth of winter wheat under P deficiency conditions and modelling of P and K uptake. Soft, red winter wheat, cv. Caldwell, was grown at the Purdue Agronomy Farm in Indiana, USA on a loess soil with contrasted manurial history for 25 years. On this soil it was possible to sample for roots manually with a 1 inch auger which gave comparable rooting densities to those found with the more usual 7 cm diameter cores taken hydraulically. In the absence of P total root length in the top 40 cm of soil at anthesis was 10 km m^{-2}, less than half

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that in the fully fertilized soil. Measurement of soil buffer capacity, solution concentration and moisture content were used in the Cushmann-Barber model (Barber (1984) *Soil nutrient bioavailability,* New York: Wiley, p. 114) to predict P and K uptake. Virtually all uptake occurred during May, plant P composition was relatively constant at 0·2% in dry matter. Predicted P uptake was some 20 times less than observed, probably because root hairs, mycorrhizae and release of P solubilizing agents by roots are important under conditions of P deficiency; however none of these are allowed for in this model. K uptake was over-predicted four times. (Barraclough with Professor S. A. Barber, Purdue University, Indiana, USA)

Nutrient fluxes into wheat roots growing in solution culture. Determining nutrient fluxes into crops grown in the field is difficult and solution culture allows easier measurement of the factors affecting fluxes, although it is not always easy to directly relate data from the latter to field conditions. However, work done recently in solution culture showed that depriving 17 day-old winter wheat plants of N for five days increased root weight but decreased plant growth and P and K inflows into roots. On restoring the N supply, no compensatory increase in inflows occurred, including that of N, presumably because inflows were being controlled by the current growth rate of the plant. (Barraclough with Professor S. A. Barber, Purdue University, Indiana, USA)

Root observation tubes in field studies. Comparative studies of root growth using mini-rhizotrons and soil coring (*Rothamsted Report for 1985*, 169) were continued using the winter wheat crop grown in the droughting experiment under the mobile shelter (see p. 47). Minirhizotron data showed that maximum root counts were found in the subsoil (typically 40–80 cm deep) rather than in the topsoil; that root counts at anthesis were greater for February- than for November-sown crops, and were greater for droughted than irrigated crops. These observations remain to be verified from the core samples, but they are the opposite of past experience based on coring. Good correlations do exist between root counts by minirhizotron and rooting density by coring for samples taken from the subsoil, but the relationships are curvilinear. (Barraclough; Kent and Green)

Plant composition and nutrient uptake

The usefulness of expressing phosphorus concentrations in crops on the basis of tissue water. New insights into the behaviour of nitrogen and potassium concentrations in crops were obtained when the concentrations of these nutrients were expressed on the basis of tissue water (Leigh & Johnston, *Journal of Agricultural Science, Cambridge* (1983) **101,** 675–685 and 741–748; (1985) **105,** 397–406). Therefore the effects of recalculating P concentrations in spring barley (*Hordeum vulgare* cv. Georgia or Julia) on the basis of tissue water were also investigated. Whereas percentage phosphorus (%P) in dry matter declined during growth, P concentrations in tissue water declined initially but then increased. The rate of increase became more rapid during senescence. This pattern of an initial decline followed by an increase is similar to that observed for N concentrations expressed on the basis of tissue water (Leigh & Johnston, *Journal of Agricultural Science, Cambridge* (1985) **105,** 397–406). By analogy with the situation for N, it may reflect changes in the relative proportions of leaves and stems which, possibly, maintain appreciably different concentrations of P in tissue water. The rate at which nitrogen and water were supplied induced differences in %P in dry matter but these effects were much smaller when P concentrations were expressed on the basis of tissue water. Like %P in dry matter, P concentrations in tissue water were lower in crops grown in a soil that had not received P since 1852. Phosphorus concentrations in tissue water may be useful for assessing the P status of crops and may have some advantages

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over %P in dry matter because they are less sensitive to factors such as N fertilization. (Leigh and Johnston)

Investigation of anion transport across the tonoplast. Investigations have continued of the effects of anions on pyrophosphate-dependent proton transport in vesicles of tonoplast isolated from oat roots (*Rothamsted Report for 1985,* 169). The pyrophosphatase that catalyzes proton transport is unaffected by anions, therefore, any effects of anions on proton transport can be interpreted in terms of secondary anion transport mechanisms at the tonoplast.

When using the pH-sensitive fluorescent probe, quinacrine, both chloride and nitrate stimulated pH gradient formation to a similar extent while sulphate and malate were less effective. The anions dissipated membrane potential with the same order of effectiveness that they stimulated pH gradient formation. This suggested that the membranes contained a selective anion channel through which anions were transported in response to the membrane potential generated by proton transport, causing dissipation of the membrane potential and stimulation of pH gradient formation.

With quinacrine, there was no evidence for the presence of a nitrate/proton symport that utilized the pH gradient to export nitrate from the vesicles (as suggested by Blumwald & Poole, *Proceedings of the National Academy of Sciences, USA* (1985) **82,** 3683–3687). However, with another fluorescent pH probe, acridine orange, pH gradient formation was always lower with nitrate than with chloride, consistent with the presence of a nitrate/proton symport. The inconsistency of these results suggested that one of the pH probes was giving artefactual results. The accumulation of ^{14}C-methylamine was used to measure pH gradient formation, and both pH probes faithfully reported the pH gradient formed in their presence. However, when both acridine orange and nitrate were present the gradient was smaller. The possibility of an inhibition of nitrate uptake into the vesicles or a stimulation of the nitrate/proton symport by acridine orange is being investigated. (Pope and Leigh)

Effect of abscisic acid on wheat root turgor. At a concentration of 25 μM, abscisic acid (ABA) increased turgor by up to 450 kPa in cells located within 1 cm of the tip of wheat roots. At 4 to 5 cm from the root tip the same concentration of ABA reduced turgor in the peripheral cells (epidermis and outer cortical cells) to zero or close to zero whilst that in the inner cells was increased. Subsequently the effect of ABA was characterized by measuring changes on osmolality of sap extracted from roots. ABA increased osmolality and the effect saturated at 5 μM ABA. The increase in osmolality took about 4 h and was partly the result of reducing sugar accumulation. Levels of inorganic cations were not affected. Root growth was inhibited at ABA concentrations that caused turgor to increase. (Leigh and Jones (SERC/CASE Student) with Dr A. D. Tomos and Prof. R. G. Wyn Jones, University College of North Wales, Bangor)

Grain quality

Wheat grain quality. Work on grain quality, first reported last year (*Rothamsted Report for 1985,* 170), was repeated this year to determine the effect of season. Sieve size fractions (<1·0, 1·0–2·0, 2·0–3·5 and >3·5 mm) and specific weights (kilograms per hectolitre) were determined on samples of grain from Broadbalk (cv. Brimstone), a straw-incorporation experiment at Rothamsted (cv. Mission) and a multifactorial experiment at Saxmundham with two cultivars (Galahad and Moulin) grown after either beans or wheat. Specific weights were determined on the 1·0–3·5 mm fraction at 87% dry matter.

The proportions of grain in the various sieve size fractions were similar to those in 1985. The amounts of trash (<1·0 mm) and very large grain (>3·5 mm) were very small. There

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was little grain in the 1–2 mm fraction, probably because there was no water shortage during grain fill.

On Broadbalk grain yields ranged from 1·1 to 9·9 t ha^{-1} and 95–97% of the yield was in the 2–3·5 mm fraction except where K had not been applied since 1843 (91–93%). Mean specific weight of the first wheat after a two-year break was 77·4 kg hl^{-1}, of the ninth wheat 75·6, and of the thirty-fifth wheat 74·9. Unlike last year, increasing spring-applied N from 48 to 192 kg ha^{-1} increased specific weight (from 74·8 to 77·4 kg hl^{-1} on average); applying more N (up to 288 kg ha^{-1}) had no effect. Where K had not been applied since 1843 specific weight of the continuous wheat was again decreased by about 5 kg hl^{-1}.

Shallow incorporation of straw and stubble or stubble alone compared with burning had little effect on yield and the 2–3·5 mm fraction was about 97%. Specific weight was always large, 78·5 and 79·0 respectively after incorporation of straw and stubble or stubble only, and 80·0 kg hl^{-1} after burning. Where both straw and stubble were incorporated, specific weight was larger after early than after later cultivation (79·4 vs. 77·6) and larger without than with 50 kg N ha^{-1} in autumn (79·1 vs. 77·9). Like last year, aphicide had no effect on specific weight, but, unlike last year when values were smaller, neither did fungicide.

At Saxmundham, grain yields ranged from 3·50 to 10·24 t ha^{-1} and the amount of grain in the 2–3·5 mm fraction (96%) was about the same as in the other experiments. Specific weight (kg hl^{-1}) was significantly larger after beans (75·3) than after wheat (74·1) and with 60 kg N ha^{-1} in March (75·1) than without (74·4). As last year pathogen control increased specific weight (74·1 to 75·3) but rate of N in April had no effect on it nor did cultivar.

Specific weights were on average much larger in 1986 than in 1985. Some treatment effects, but not all, in 1986 differed from those in 1985. Rate of N had no effect on Broadbalk in 1985 but it did in 1986; it had no effect at Saxmundham in either year. Fungicide increased specific weight in the straw incorporation experiment in 1985 but not in 1986; it gave a small increase at Saxmundham in both years. Only on the lightest soils prone to K deficiency is the effect of K reported on Broadbalk likely to be repeated. (Penny and Hewitt)

Micronutrients in soils and crops

Effects of metals on establishment and nitrogen fixation by white clover. Decreased yields of clover grown in the field on metal-contaminated sludged soil have been reported previously (*Rothamsted Report for 1985,* 168). Further experiments in pots in the glasshouse used a range of metal concentrations produced by mixing high- and low-metal soils collected from the field experiment, in various proportions. Using ^{15}N techniques, the small white nodules which formed on roots growing in metal-contaminated soils were shown not to fix nitrogen gas. Yields after six weeks were halved and nitrogen fixation became negligible when soil metal levels were about the current UK extractable zinc equivalent for zinc, copper and nickel in soil. The corresponding total metal concentrations for Zn, Cu, Ni and Cd were 330, 99, 27 and 10 mg kg^{-1} respectively. These concentrations are also less than the likely mandatory EC maximum soil metal limits for sludged soils except for cadmium which was approximately treble the limit value. (McGrath, Giller and Brookes)

Phosphate fertilizers

The importance of water-soluble phosphate in phosphate fertilizers. Field experiments using spring barley (Klaxon) and maincrop potatoes (Pentland Crown) tested three fertilizers with 59%, 73% and 95% water-soluble phosphate and an additional fertilizer of 94% WSP in 1986, as part of a three-year programme funded by Norsk Hydro Fertilizers Ltd to assess the importance of 'water solubility' in P fertilizers. In 1986 barley also tested the residual P value from the 1985 potato experiment.

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In 1986 barley testing fresh P fertilizer showed a marked response to both percentage water-soluble phosphate (%WSP) and application rate (20, 40 and 60 kg P_2O_5 ha^{-1}) early in the season but this effect disappeared by harvest, and grain yields of about 6 t ha^{-1} showed only a slight response to rate of P. In the residual P experiment barley yields increased as bicarbonate-soluble P in soil increased from 5·0 to 33 mg kg^{-1}; there was no further increase in yield up to 47 mg kg^{-1}. In both years both crops have responded more to the amount of P applied than to %WSP.

Tests on laboratory-made fertilizers, ranging from 0–100% WSP (the insoluble component was dicalcium phosphate), using ryegrass grown in pots in the glasshouse have confirmed the negligible yield response to %WSP above 40% on soils from the Rothamsted Farm. This contrasts with results obtained by Norsk Hydro Fertilizers Ltd on other soils and techniques for conducting pot experiments are being compared. (Copestake and Johnston with Dr G. A. Paulson and Dr I. R. Richards, Norsk Hydro Fertilizers Ltd)

Potassium reserves in soils

Potassium balances in long-term experiments. Potassium balances from the long-term experiments on the Rothamsted and Woburn Reference Plots and the Rotation I Experiment at Saxmundham are being compared with laboratory analyses of K in the soils. Estimates of readily available and short-term reserves of K are determined by extraction with calcium resin; concentrated HCl is used to determine long-term reserves, whilst K exchangeable to M ammonium acetate is also being measured. Results so far show that, although there is a good relationship between exchangeable K and positive and negative K balances, the amounts are not directly proportional because the exchangeable fraction is very well buffered by a non-exchangeable reserve of K. Indications are that, on soils which receive some K fertilizer, any deficit between this and the K required by the crop is made up from short-term reserves of residual K from past fertilizer dressings. On soils that receive no fresh K, the K taken up by the crop comes equally from the short-term reserves and from the weathering of K-bearing minerals in the soil. (Goulding and Johnston; Poulton)

Potassium reserves in some Kenyan soils. The potassium reserves of five soils from semi-arid regions of Kenya are being estimated by extraction with calcium resin. The effect on K release of the intermittent rainfall and intensity of drying experienced by such soils is being tested by submitting the soils to a pre-treatment consisting of a series of wetting and drying cycles. Preliminary results suggest that all of the soils have adequate exchangeable and short-term reserves of K, which does not accord with existing knowledge of the clay minerals in these soils. The minerals identified in two of the soils were predominantly kaolinite and amorphous materials, which should contain little or no K. The clay mineralogy is therefore being re-examined. (Goulding with Dr J. Onchere, visiting worker)

Nutrient reserves in acid upland soils under forestry. Little is known about nutrient reserves and their rate of release in acid upland soils in Britain. As a beginning to understanding this problem, the effects of forestry are being studied on a stagnopodzol soil at Beddgelert Forest, North Wales. The site is managed by the Institute of Terrestrial Ecology and the Forestry Commission. The effects of harvesting only the trunk of the tree (conventional or clear felling) and whole tree harvesting (in which the entire tree is removed) are being compared. The soil was first sampled before felling in 1984 and analysed for exchangeable and short-term reserves of K by extraction with calcium resin, and for long-term reserves of K, Ca, Mg, P, and trace elements by extraction with concentrated HCl. Nutrient fluxes since felling suggest the movement of a pulse of K through, and immobilization of P in, the soil under clear felled but not whole tree harvested plots. (Goulding; Howe with Dr M. Hornung, Institute of Terrestrial Ecology, Bangor)

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UK Precipitation Composition Monitoring Network

A national network of 60 sites monitoring precipitation, organized by the Warren Spring Laboratory of the Department of Trade and Industry, will provide information on the concentration and deposition of acidity and other major ions in precipitation over the whole country. Weekly sampling from standard bulk collectors estimates both wet and some dry deposition. Samples from Broom's Barn and Woburn are analysed at Rothamsted and the data sent to Warren Spring for addition to the database, which will be available to all participating organizations.

The network came into operation at the beginning of 1986. Two interlaboratory comparisons of analytical data have been made to ensure data comparability. Preliminary maps of H^+, non-sea SO_4-S, and NO_3-N concentration for January–June 1986 have been prepared; the full year's data for 1986 will be published in the spring of 1987. (Goulding; Howe)

Soil acidification during more than 100 years on Park Grass and Geescroft

Changes in the pH of soil samples taken periodically from unlimed plots of the 130 year-old Park Grass Experiment (permanent grassland) and from the 100 year-old Geescroft Wilderness (mainly deciduous woodland) show how acidification has progressed on these sites. Each soil is now at, or is approaching, an equilibrium pH value; that on Geescroft is more acid than that on Park Grass. These values depend on acidifying inputs, on the buffering capacities of the soils and on the vegetative cover. The relative importance of the various sources of acidity: atmospheric deposition, crop growth and nutrient removal, soil-derived natural sources, and, where applicable, fertilizer additions, has changed as the soils have become more acid. Acid rain (wet deposited H^+) is a negligible source and has been throughout the course of the experiments. Total atmospheric deposition, including dry-deposited SO_2 and NO_x, and NH^+_4 in rain which may be nitrified, may comprise up to 30% of acidifying inputs at or near neutral soil pH values, and up to 70% as soil pH decreases. At low soil pH these inputs cause little soil acidification, however, because the lime potential of the rain is greater than that in the soil. Excepting fertilizers, the major causes of soil acidification at or near neutral pH values are the natural inputs of H^+ from the dissolution of CO_2 and subsequent dissociation of carbonic acid, and from the mineralization of organic matter.

Under grassland, single superphosphate and small amounts of sodium and magnesium sulphates have had no effect on soil pH, potassium sulphate slightly increased soil acidity, but nitrogen fertilizers had a marked effect. Against a background of other acidifying inputs, nitrogen as ammonium sulphate decreased soil pH up to a maximum of 1·2 units at a rate in direct proportion to the amount added. This was almost entirely caused by nitrification of NH^+_4. In contrast, nitrogen as sodium nitrate, increased soil pH by between 0·5 and 1·0 units for reasons which are not clear, although leaching of Na in place of Ca may be involved.

The difference in pH between unmanured grassland and deciduous woodland has consequences for both soil pH and, probably, the pH of any drainage, if it is considered that one option for land not required for agricultural production would be afforestation, even with deciduous trees (Johnston and Goulding; Poulton)

Straw incorporation

There has now been a succession of dry autumns and as a result those farmers who have tried straw incorporation appear to have experienced no major problems. However, experiments measuring the long-term effects of different methods of straw disposal on the growth of autumn sown crops continue to monitor changes in yield and, where necessary, explain them (see also p. 33). In all our experiments straw is chopped before incorporation. For cereals

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all our results so far indicate that one of the major problems with shallow straw incorporation is the germination and survival of shed grain from the previous harvest. Indeed some of the yields recorded here have been affected considerably by volunteers but we have no way of knowing if more of the sown crop would have survived if there had been no volunteers. Problems with cereal volunteers in late sown oilseed rape were experienced this year but for rape the main problem is rapid disposal of straw and an experiment comparing six straw disposal treatments is described here.

Methods of alleviating the adverse effects of straw. Straw and stubble incorporation continues to be compared with stubble incorporation and straw and stubble burning on a clay soil (Lawford series) at Northfield, Oxfordshire, where the treatments have been cumulative since 1979.

Results during 1980–84 showed that, compared with burning, unsatisfactory yields resulted from direct-drilling into stubble and chopped straw or where incorporation was very shallow. Consequently, in autumn 1984, three depths of incorporation, 5, 15, 25 cm and direct drilling were tested (*Rothamsted Report for 1985*, 172) and these treatments were repeated in autumn 1985. Plant population from the sown crop was satisfactory on all treatments in early December except where stubble and straw had been incorporated only to 5 cm. On these plots, germination of shed seed from the previous crop made it impossible to estimate sown plants. The very cold and dry weather in February severely thinned crops direct drilled into stubble and straw and these had to be resown. Plant loss was attributed to both shallow rooting into surface litter and damage by birds which fed preferentially on these plots.

Yields of grain following direct drilling and the 5, 15, 25 cm depths of cultivation after burning were 7·8, 7·6, 7·2, 7·1 t ha^{-1} respectively. Following cultivation to 5, 15, 25 cm, yields were 6·5, 7·2 and 7·3 t ha^{-1} respectively with chopped straw and 7·2, 7·2 and 6·2 t ha^{-1} with stubble only. As in 1985, yields were closely similar irrespective of straw disposal method when the depth of cultivation was 15 cm. Leaf stripe (*Cephalosporium gramineum*), which first appeared in 1983, was measured in June 1986 and was more severe where straw was present, although the level of infection was less than in 1985. (Christian and Bacon)

Effects of different amounts of straw. Yields of winter wheat, cv. Avalon, have been measured after three cumulative annual applications of 0, 5, 10, 15 or 20 t ha^{-1} finely chopped straw. All plots were rotary cultivated to 7 cm and then tine cultivated to 15 cm.

In the first year (1984) 5 t ha^{-1} of straw increased yield by about 4% more than control (11·6 t ha^{-1}), but with more than 5 t ha^{-1}, yield declined compared with control by 7% for each 5 t increment of added straw. In 1985 and 1986 the effects were more variable and none of the differences were significant. In 1985 both 5 and 15 t ha^{-1} of straw gave the best yields, average 6·4 t ha^{-1}, about 9% heavier than control; yields with 10 or 20 t ha^{-1} were similar to control. In 1986, 20 t ha^{-1} straw gave the best yield (9·7 t ha^{-1}) and 10 t ha^{-1} straw the least (8·8 t ha^{-1}). Yields on the control, 5 and 15 t ha^{-1} plots were closely similar, about 9·5 t ha^{-1}. Averaged over the three years, the addition of 5 t ha^{-1} of straw has given a small yield benefit compared with no straw added whereas amounts of straw in excess of 5 t ha^{-1} have adversely affected yield largely as a result of the large effects in the first year. (Christian and Bacon)

Straw disposal before winter oilseed rape. To drill winter oilseed rape early requires rapid disposal of straw from the preceding cereal. Various combinations of straw disposal and soil cultivation have been compared. The treatments were: (1) straw burnt, seed direct drilled. All the remaining treatments were conventionally drilled: (2) straw burnt and soil tine cultivated (3) straw burnt and soil ploughed (4) straw incorporated by tine cultivation (5) straw incorporated by ploughing (6) straw removed and soil tine cultivated. Oilseed rape, cv.

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Bienvenu, was sown at 8 kg ha^{-1} on either 22 August or 9 September with either none or 50 kg N ha^{-1} applied on 20 August to the seedbed. After ploughing, seedbeds could not be prepared in time for sowing on 22 August because of very dry conditions, so all ploughed plots were sown on 9 September. Owing to the dry conditions the later sown crop emerged in two bursts, the majority of plants appeared after rainfall on 7 October. This caused a delay in the application of herbicide to control cereal volunteers.

The number of established plants were counted on 13 September (early sown) and 31 October (late sown); and again on 12 March. In autumn differences in plant population were not significant, 123 vs. 110 plants m^{-2} on early- and late-sown crops respectively; however, many of the late-sown plants which emerged late were very small. By 12 March numbers had declined to 112 plants m^{-2} on early-sown plots; but winter kill of the late-sown crops was severe (up to 92%), especially where straw had been chopped and soil cultivated before sowing. Plots which had been ploughed retained more plants than plots tine cultivated, 68 vs. 26 plants m^{-2} respectively.

Early sown rape yielded well, more than 4·0 t ha^{-1} at 90% dry matter on treatments 1, 2 and 6 but where straw had been incorporated by cultivation the yield was 3·88 t ha^{-1}. Late-sown rape yielded less than early-sown but more than might have been expected from the small numbers of plants in March. The largest yield, 3·90 t ha^{-1}, of late-sown rape was after straw burning and ploughing, equivalent to that obtained by early sowing, but where straw had been incorporated yield was only 1·19 t ha^{-1}. Seedbed N increased yield by only 0·09 t ha^{-1} for both early- and late-sown crops. Oil content of the early-sown rape was not affected by straw treatments; but there were significant decreases up to 8·7% oil in dry matter for late-sown rape when straw had been incorporated.

Many of the decreases in yield occurred when rape was sown later and may be a direct consequence of the dry autumn and severe winter kill. However, both early- and late-sown rape yielded less when straw was incorporated by tine culitvation than for all other treatments. The effect of late sowing and the possibility of severe winter kill needs further study. (Darby)

Toxin production and oxygen demand. The consequences of the presence of straw in the seedbed have been investigated further both in the field and the laboratory. In the laboratory the influence of soil type was studied using packed columns 1 m deep. At 10°C the oxygen demand of straw equivalent of 20 t ha^{-1} incorporated in a 10 cm layer was not enough to exceed supply in either a clay soil (Lawford series) or sandy loam soil (Stackyard series). Except when seeds were placed in close contact with straw, effects on shoot growth were attributed to plants and microbes involved in straw degradation competing for nitrogen.

Where straw was incorporated into soil in the field, it had no effect on the depth from which water was extracted by winter wheat confirming previous conclusions that straw had little effect on root growth. Where the seed was direct drilled into chopped straw plant populations were decreased and both shoot growth and water use efficiency were less than where straw had been burnt.

On the clay soil, the hydraulic conductivity of unsaturated soil was increased by the presence of straw. This could suggest an improvement in the internal structure of the peds although it is possible that there were more large pores in soil where straw was burnt. Future work will concentrate on the effect of straw on soil physical conditions for crop growth. (Goss, Smallfield and G. Williams)

Transport processes in soils

Groundwater flow. Permeable substrata can have a big effect on groundwater behaviour. High water tables and ponding of the soil surface result not only from intensive rainfall but

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also from upward seepage from such substrata under an artesian head. Drainage installations are used to maintain water tables at a desired level, and their design has been calculated by solving the groundwater flow problem using potential theory. The empirical equation

$$d = h_a - (h_a - H_m) \exp(1{\cdot}65\ D/h_a)$$

fits well the analytical solution obtained by the method of conformal transformations. It gives the position of drains, spaced 2D apart and located at a height d, that would maintain the water table at a height H_m when the artesian head is h_a with the level of the substratum taken as the datum. (Youngs)

When water seeps vertically from a ponded surface through both the topsoil and a more permeable substratum, the latter, although at a negative soil-water pressure, may be unable to desaturate as the water table falls if there are no air entry channels. Using laboratory soil models, we have shown that the absence of air channels causes larger seepage rates and the development of larger negative soil-water pressures. The situation occurs in rice paddy fields, where water consumption can be reduced if the lower more permeable soil is vented to allow air entry. (Youngs and Marei)

Hydraulic conductivity measurements. The hydraulic conductivity of a soil is sensitive to changes in pore sizes and so is a good measure of soil structure. *In situ* measurements of the hydraulic conductivity of the saturated soil near the surface can be made using ring infiltrometers. The analysis of the data is complicated by the flow being both horizontal and vertical. Using similar media theory that gives a single relationship at early times between the infiltration and time scaled according to this theory, we have developed a technique of obtaining the hydraulic conductivity using these rings when the water has moved only a short distance into the soil. The method thus samples the soil very close to the surface. Field results show that large rings must be used to sample a representative area. A further analysis of the flow problem takes into account the depth of ring penetrating into the soil. The use of tension infiltrometers allows the structure to be more fully investigated by excluding water movement from the larger pores when water is supplied at a negative pressure head. (Youngs)

Drainage and cultivation: the Brimstone Experiment. This field experiment, begun in 1978 (*Rothamsted Report for 1985,* 174), now compares yields of crops grown (a) without and with a mole and pipe drain system; (b) ploughed conventionally versus direct drilled. Each plot is separated from its neighbours by polythene barriers to 1.1 m and interceptor drains. Surface water run-off and flow in soil and mole channels are measured. The volume of drainage water and its content of nitrate are also determined.

Winter wheat, cv. Avalon, sown at 426 seeds m^{-2} in October 1985 followed oilseed rape (*Rothamsted Report for 1985,* 174). On undrained plots the water-table had risen to the A horizon by mid-December. On drained land some rainwater moved by bypass flow directly to the mole drains during late-November and December and this delayed the rise of the water-table to mole-drain depth (approx. 55 cm) until mid-January. Nevertheless the differences in depth to the water-table lasted for 42 days, which, from previous experience, was expected to decrease grain yield by 10% on undrained soil. However, there was no significant effect of drainage, probably because the weather in February was unusually cold with too little snow to protect the young plants. There was an effect of tillage on shoot development by the end of April: the crop established after direct-drilling had 1000 shoots m^{-2} whereas that after ploughing had only 840 m^{-2}; this difference did not produce more fertile ears. Yield averaged 7·9 t ha^{-1}.

The variation of hydraulic conductivity with depth was investigated for one plot of each treatment. In the horizons above 50 cm the conductivity at water potentials from -1 to -1500 kPa was greater by up to half an order of magnitude in direct-drilled soil than in

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ploughed soil. This confirms previous evidence for improved pore conductivity in soil not subject to annual ploughing (*Journal of Agricultural Engineering Research* (1984) **30,** 131). In the top 10 cm the conductivity was larger in drained than in undrained land, the effect also was about half an order of magnitude. Comparisons at 30 cm were confounded by the presence of a compacted layer in the drained plots. No significant treatment effects were found below 50 cm. When the soils were saturated the variation in hydraulic conductivity values between locations was about an order of magnitude greater in this Denchworth series soil than in the Evesham soil at Silsoe (p. 162), i.e. the Denchworth soil was much less uniform than the Evesham.

In November there was 110 kg N ha^{-1} as nitrate in the soil to 60 cm deep, some 30–40 kg more than previously found at that time. It is not clear whether this was because of residual nitrogen following oilseed rape or above average mineralization in the dry autumn. Before the spring N top-dressing was applied in April, and after 170 mm drainage, the soil contained between 200 and 350 kg N ha^{-1} as nitrate with 18% more in undrained plots than in drained ones, and 38% more in the ploughed soil than in direct-drilled soil. Denitrification losses in spring after top-dressing with 130 kg N ha^{-1} were small, ranging from 3·0 to 9·1 kg N ha^{-1} (p. 148). The contribution of different cultivation and drainage practices to these differences in inorganic soil nitrogen is worthy of much further study. (Goss, Christian, Howse, Bacon with Dr P. Colbourn, Welsh Plant Breeding Station and Mr G. L. Harris, Field Drainage Experimental Unit)

Modelling transport of water and heat in tilled soils. An important task in soil physics is to predict the dynamic variation of soil conditions in response to the incoming radiation and rainfall and to understand how tillage can modify these conditions to best suit the establishment of plants. At this phase of development the important properties to be predicted are the water content and temperature of the seedbed and the complex interaction between these variables. The physical mechanisms governing different parts of this system are now well enough understood for deterministic models to be formulated but few incorporate a sensitivity to the effects of tillage. One such model that appears adaptable for tillage work is CONSERVB (Lascano & van Bavel, *Soil Science Society of America Journal* (1982) **47,** 441–448) and this is currently being tested using the Phoenix computer at the University of Cambridge. However, a theoretical derivation of the variation in hydraulic conductivity and moisture potential with both water content and soil depth, which are critical functions in this model, is inadequate from basic soil properties, particularly for tilled soils. Our comprehensive *in situ* measurements of these functions and other soil properties for both a silty clay loam and a sandy loam soil provide the necessary data to verify CONSERVB and use it predictively. (North)

Soil structure and tillage

Work to understand the basis of structure, strength and stability of soil continues. The study covers the spectrum from interparticle forces in clays to the behaviour of bulk soils under different tillage systems.

Interparticle bonding. The strength and stability of soil and its behaviour under cultivation depend ultimately on forces between individual particles. These forces can be related qualitatively to the shear modulus of pastes of the clay fraction. The way in which the shear modulus G, changes with time seems to be characteristic of all clay pastes, and can be modelled as

$$G = A - \frac{B}{1 - Dt}$$

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where t is the time and A, and B and D are parameters to be determined. The values of D are typically 0·05–0·10, and G stabilizes after about one hour.

Shearometer measurements have been used to examine the effect of iron oxides on the stability of soil structures in soils where the silicate clay minerals are similar but the amount of iron oxide varies. The shear modulus decreased with increasing proportions of extractable iron and appears to depend on the bonding of the clay by the iron oxides into microaggregates. (Piper and Chandler)

Shrinkage forces. Shrinkage and swelling of clay soils are important soil-forming processes in the field. In particular, cracking often occurs during shrinkage on drying because of tensile stresses generated in the body of the clay. A theory for predicting such stresses has been developed. It shows that a system of tensile stresses acting in a body of clay subjected to a negative pressure in the soil water (as in drying) can be replaced by an appropriate system of compressive stresses and zero soil-water pressure without altering the state of the clay up to incipient cracking. This transformation allows the application of theoretical methods that are available for a wide range of compressive-stress systems.

When remoulded clay bars were constrained during drying from shrinking in the longitudinal direction but free in the other directions the theory predicted, and the measurements confirmed, that they would crack at a water content dependent on the type of clay but independent of the initial water content. Calculations of the tensile stress generated in this stress system for seven remoulded clays (using published data) gave values in the range 0·15 P to 0·22 P; where P is the soil-water suction inferred from the water content assuming isotropic compression. Further applications under investigation include vertical cracking in the field and disintegration of soil crumbs. (Towner)

Anisotropic shrinkage. The physical properties of clay soils are generally assumed to be isotropic. However, when cylindrical samples of remoulded kaolinite were compressed uniaxially and then allowed to dry the rate of linear shrinkage in the pre-compressed direction was smaller than in the other two directions. (Towner; Dailey)

Cultivation and physical properties of seedbeds. Cultivating a seedbed in autumn rather than in spring improved establishment of a spring-sown vegetable crop on light soil (*Rothamsted Report for 1985*, 176). The improvement in both emergence time and final percentage emergence of onions was greatest for seeds sown into dry soil. This was thought to be caused by either an improved supply of water from deeper soil layers to the germinating seeds, or better thermal insulation leading to reduced water losses by evaporation. However, *in situ* measurements in the 0–200 mm soil layer of both temperature and unsaturated hydraulic conductivity showed that differences between autumn- and spring-cultivated seedbeds were too small to verify either mechanism. The coarseness of the seedbed was found to be major factor affecting emergence through its likely influence on mechanical impedence to shoot growth. The seedbed prepared in autumn had a finer tilth and the small increase in mechanical strength when the soil dried did not impede the emergence of seedlings. (North; Patel)

Temperature and seedling emergence. The effect of soil temperature on the emergence of onions was determined by covering some plots with polythene enclosures. The average mean daily temperature, measured at 50 mm depth, was 2·7°C greater on enclosed plots during the 20 days following sowing, and the time to 50% emergence was two days shorter. Thermal time, T_A, accumulated from sowing to 50% emergence, using soil temperature at 50 mm and a threshold for growth of 0°C, was the same for both enclosed and exposed plots and thus the effect on speed of emergence was due solely to temperature differences. Values

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of T_A to 50% emergences were calculated for both covered and uncovered soils using air temperatures measured at 50 mm above the soil surfaces and meteorological screen temperatures. Values were the same for both types of plot but were 8 and 25% smaller respectively for the two methods of calculation than those using soil temperatures at 50 mm. Use of air temperatures in these calculations thus considerably underestimates thermal contributions to emergence and cautions against their adoption for quantitative growth studies in seedbeds. (North; Patel)

Simplified tillage and controlled traffic. Decreasing the depth of tillage can reduce costs, particularly by increasing work rates but continuous shallow cultivation may not remove compaction by wheels so that soil structure could deteriorate and more draught might be required for tillage later. The benefits of keeping all wheelings within well defined permanent tramlines is being investigated at the AFRC Institute for Engineering Research, Silsoe, Bedfordshire (IER). Problems with manganese nutrition last year (*Rothamsted Report for 1985*, 176) were overcome with a foliar application in 1986. Grain yields of winter wheat averaged 6·7 t ha^{-1} and were similar on shallow cultivated and direct-drilled land whether the plots received normal or zero wheeled traffic.

The hydraulic conductivity at saturation was determined as an indirect method of identifying soil structural conditions that might impair root development. Measurements with horizontally inserted piezometers were made over winter in the 0·5 to 2 m depth. Values of conductivity from 20–40 mm day^{-1} were obtained for depths from 0·5 to 0·9 m. Over the next 0·2 m the values sharply declined to only 0.05 mm day^{-1}; then from 1·1 to 2 m there was a steady decline in values to 0·01 mm day^{-1}. Water extraction by wheat roots has followed a similar pattern and has consistently been greatest above 1 m with little extraction taking place below 1·4 m. The consequences for soil physical conditions and root development of tillage using a tractor or the gantry system developed at the IER will be examined next.

In laboratory studies with a silt loam soil, the oxygen flux density that limited the extension of wheat root axes at 10°C was 0·9–1·0 mg oxygen cm^{-2} s^{-1}, similar to values reported for oats. (Goss, Howse, Youngs, Powell with Mr W C T Chamen, IER)

Spatial analysis of soil structure. New measures to describe the patterns of fissures in soil have been developed by studying the structure of cracking clays. Soil, impregnated with resin containing fluorescent dye, has plane faces cut through it which are photographed under UV light, so that fissures wider than about 50 μm appear as black traces on negatives. By placing linear probes across the traces and measuring the distances between successive intersections the distribution of spacings is obtained and can be modelled. In the soil examined (Windsor series) the fissures were essentially planar with an exponential distribution. The pattern was anisotropic with fissures preferentially aligned parallel to the contour of the land and dipping into the hill slope at angles ranging from about 25° to 75° to the horizontal.

The topology of fissure patterns has been studied by cutting close-spaced serial sections which are then photographed as above. The pattern on each negative is skeletonized, each disjoint element in it identified and labelled and then elements tracked from section to section. The numbers of new elements appearing or old elements disappearing are counted, and the counts regressed against the volume of soil spanned by the sections to estimate the numerical density of the fissures. Equally important in the topology of pore patterns is their connectivity. This is measured in like manner by identifying all the loops in the pattern and counting them. Again the connectivity density is obtained by regressing the counts against the volume spanned. Stable estimates of numerical density and connectivity density were obtained for the subsoil of the Windsor series, they were approximately 35 cm^{-3} and 300 cm^{-3} respectively and for the Swanwick series 75 cm^{-3} and 190 cm^{-3}. (R. Webster and Scott, NERC/CASE Student)

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Soil mineralogy

Mineralogy of iron rich soils. A detailed quantitative analysis has been made of the iron oxide minerals present in soils from Northamptonshire and from North Kent. The dithionite extractable iron content varied from 5% to 20% for the soils from Northants and was <2% in that from North Kent. The goethite (α-FeOOH) to hematite (α-Fe_2O_3) ratio varied also. For the Northamptonshire soils this ratio was always greater than 7:1, in the North Kent soil it was much narrower $\simeq$ 1·5:1.

Advances in our differential diffraction methods for iron oxide analysis have been made. Our revised analysis software now utilizes a greatly extended range of the diffraction pattern (1500 profile points as opposed to 300). The assumptions made seem to be valid over the whole of the angular range used and so this greatly increases the reliability of the results. Previously, the analysis has been based on computer-modified diffraction patterns from standard iron oxide samples; alternatively an *a priori* calculation of the iron oxide diffraction patterns can be made from their known crystal structures. This allows the determination of properties such as the degree of aluminium substitution in the goethite and the particle size of the iron oxides.

When analysing differential diffraction patterns it is necessary to include in the calculation a term describing the change in X-ray fluorescent background resulting from the chemical removal of the iron oxides from the soil. In essence this provides a crude X-ray fluorescence spectroscopy determination of the dithionite-extractable iron, accurate, for samples containing less than 16% extractable iron, to about $\pm 1\%$. This provides a useful check between the X-ray results and those obtained by elemental analysis.

Accurate estimation of the very small amounts of hematite (between 1 and 5% of the total clay fraction) present in the Northamptonshire soils, provides a severe test of this method. It is generally considered that soil colour is very sensitive to hematite content and we have therefore also examined the colours of these materials using a simple reflectance attachment constructed for a visible/ultra-violet spectrophotometer. Preliminary results show the expected trend. The addition of as little as 1% of hematite to a sample of geothite produces a measurable change in the spectrum, suggesting that the method is very sensitive. (Wood and Piper)

Instabilities in diffractometer alignment. Recently the potential sensitivity of X-ray powder diffraction has been greatly increased by the use of elaborate programs for analysing data and procedures such as difference diffraction methods. Good experimental technique therefore assumes greater importance. Our apparatus, which is of a type commonly used, is sensitive to fluctuations in ambient temperature and even to changes in the temperature of the liquid used to cool the X-ray tube. Both the positions and the intensities of the peaks in the diffraction pattern are altered, the changes being of order 0·001°2θ per °C and 0·3% per °C respectively. These apparently very small changes are large enough to cause serious errors, especially as many of the standard methods for compensating for the shifts, such as the use of an internal standard, may not be effective. This is because the error may be time dependent and thus affect different regions of the diffraction pattern to different extents. (Brown and Wood)

Pedological studies

Chiltern dry valley soils. The soil on the floors of chalkland dry valleys is often very variable in particle size distribution, carbonate and flint content. This is usually explained by deposition of loess and coarse flinty and chalky gravels in the last cold stage of the Pleistocene, followed by hillwash of fine soil after recent cultivation of the valley sides. However, radiocarbon dating of a buried organic horizon in a valley bottom profile near

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Medmenham, Buckinghamshire, showed that a range of very flinty deposits accumulated here during the last 2000 years. Samples from this profile and similar dry valley soils nearby were analysed for particle size distribution and mineralogy as part of our work to understand soil variability. The results suggest that the main process responsible for carrying the deposits on to the valley floor was mass movement by debris flows down the valley sides. (Catt, with Prof. J. M. Recio Espejo, Cordoba University)

Origin of loess-like sediments at Slindon, Sussex. Samples of buried soils and loess-like sediments from a Lower Palaeolithic archaeological site near Slindon, Sussex, were analysed mineralogically to help reconstruct environmental changes during the period of human occupation. The occupation site lay close to the Channel coast during a mid-Pleistocene interglacial and was sealed by flint gravels and geliflucted Clay-with-flints (weathered Readings Beds) derived from the South Downs behind the cliff during an ensuing cold period. The loess-like sediments occurring at two separate horizons were found to contain very little far-travelled silt. Most of their coarse silt fraction was probably also derived from weathered Reading Beds, from which it was perhaps concentrated by hillwash under fairly cold conditions when there was little or no vegetation on the Downs. (Catt, with Dr M. Roberts, Institute of Archaeology, London)

Strontium isotope ratios in loess. The ratio of $^{87}Sr/^{86}Sr$ in the calcium carbonate of marine limestones is strongly correlated with geological age and unaffected by recent dissolution and reprecipitation of the carbonate. We are measuring this ratio in carbonate extracted from English loess samples and underlying limestones, to test the Russian and American suggestions that loess was formed in an alkaline weathering environment involving upward migration of calcium ions from calcium-rich substrata. Although this process would help explain the distribution of loess in England and Wales, the results so far indicate that all the calcium carbonate is derived from a source with $^{87}Sr/^{86}Sr$ ratios quite unlike any of the subjacent limestones. (Catt, with Dr Lois M. Jones, Conoco Inc., Ponca City, Oklahoma)

Man-made urban soils. The uniform black deposit known as 'dark earth', which occurs on many Roman urban sites, has been analysed to determine its origin and the processes responsible for its colour. Geochemical results support the earlier physical and mineralogical evidence that dark earth is fairly homogeneous and has undergone little pedogenesis, suggesting rapid deposition and burial. Unusually large concentrations of some metals, especially Pb and Mo, indicate that dark earth could not have been used for growing crops; this conclusion is supported by pollen assemblages which indicate a wasteland flora. Our analytical results increasingly point to rapid deposition of dark earth coincident with the abandonment of urban centres during contraction of the Roman Empire. (Catt and Farrington)

Remote sensing

Short-range variation of soil and cereal crops. Within-field variation of growth and yield in cereals often results from short-range changes in soil properties, such as rooting depth and water holding capacity. At three sites in 1986 a radiometer was used to measure spectral differences in winter cereals during the growing season, and these have been related to grain yield and soil characteristics. The largest yield differences were in wheat growing on a sloping site at Theobalds Park (Hertfordshire); on London Clay near the foot of the slope, yields were on average 38% greater than on Chalky Boulder Clay at the summit. On a flat site at Weeting (Norfolk) barley yielded 29% more on shallow chalk soil than on a deep sandy soil, but at Broom's Barn the yield difference between soil types was only 3%. The radiation from the crops appeared not to be related to crop performance until within a month

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of harvest. Measurements made then, however, correlated well with the yield of grain at the first two sites. At both the best yield prediction at this time was given by the ratio of red to near infra-red reflectance. These relationships and their causes are being explored by further analyses. (Catt, R. Webster, Munden and Ashcroft)

Analytical and techniques

Analytical, isotope and sample handling sections. The Analytical Section carried out 179 000 analyses, arising from 17 700 samples, somewhat fewer than last year; 16% were done for other departments. Because of staff losses the Isotope Section no longer has any full-time staff, nevertheless 2400 analyses were done. This was many fewer than last year because alternative scintillation counters have become available. The Sample Handling Section processed 8600 samples for dry weight determination and preparation for analysis. Grain mass (1000 grain weight) was determined on many of the grain samples. (Cosimini, Robertson, Fearnhead, Cundill, Gregory, Kellerman, Thompson and P. A. Williams)

Automatic data recording. The data recording system previously described (*Rothamsted Report for 1984,* 189) has been further developed and improvements made to the logging program on which work continues. A suitable material for machine-readable barcoded labels has been found, it is tough, flexible, waterproof, and can withstand the temperatures normally encountered when drying samples. (Darby)

Oil or moisture measurement by NMR spectrometry. A Newport N4400 nuclear magnetic resonance (NMR) spectrometer with 40 and 150 ml cavities has been purchased to determine the oil content of rapeseed, sunflower and other oil seeds. This instrument is microprocessor-controlled, and of the continuous emission low resolution type. It is tuned to the resonant frequency of hydrogen contained within the oil and can discriminate between the signal obtained from hydrogen in a liquid material (oil or water) and that bound in a solid (carbohydrate). Consequently, oil content may be determined in whole seeds after the removal of moisture by drying. In addition the moisture content of seeds, e.g. wheat, barley and oats, containing little or no oil can be determined. The results agree well with those from oven drying. Tests have shown that the moisture content of soils can also be measured. Sample weights are accepted directly from a balance connected to the instrument, and the time for each analysis is about one minute. The instrument can be linked directly to the automatic data recording system. (Darby)

Staff and visiting workers

A. E. Johnston was appointed Acting Head of Soils Division on 10 February 1986.

The Department was saddened by the tragic death on 7 October, the result of a road accident, of Jennifer Piper, who had been with us at Rothamsted for three years.

P. D. Robertson took voluntary premature retirement, F. V. Widdowson and G. Brown retired, R. N. Le Fevre transferred to the Computing Unit, G. J. Smith, F. K. G. Henderson, J. R. Sanders, G. A. Rodgers and D. Brockie all left and Lisa Nicholls resigned.

The following were appointed: G. J. Bland to work on the nitrogen prediction system, A. J. Macdonald to work on leaching of nitrate, both under a MAFF Open Contract Scheme, and Margot Ewens, funded by Borax, to work on new forms of boron fertilizers.

G. W. Cooke gave a course of six lectures in Madrid, attended a Workshop in Muscle Shoals, Alabama, on the use of fertilizers in Africa organized by the International Fertilizer Development Center and presented a paper at the International Plant Nutrition Colloquium held in Rockville, Maryland, USA, and with A. E. Johnston presented papers at the 13th Congress of the International Potash Institute held in Reims, France.

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P. B. Barraclough returned after spending six months as a visiting scientist at Purdue University, Indiana, USA. He gave seminars there and at Michigan State University, East Lansing, and visited the University of Illinios. D. S. Jenkinson gave a paper and helped organize the joint International Soil Science Society (ISSS)/International Humic Substances Society symposium on 'Dynamics of Organic Matter in Soil' at the 13th International Congress of the ISSS in Hamburg, Germany. R. Webster, P. B. Barraclough and K. W. T. Goulding also presented papers, and J. A. Catt was nominated Chairman of the ISSS Working Group on Palaeopedology. D. S. Jenkinson also gave lectures at the Royal Veterinary and Agricultural University, Copenhagen and at the Statens Planteavls-Laboratorium in Lyngby, Denmark and together with A. E. Johnston, presented papers to the INTECOL Symposium on 'Soil Organic Matter and Soil Productivity' at Flen, Sweden. R. Webster participated in the Working Group of ICSU Terrestrial Ecosystems in Montpellier, visited research laboratories of INRA and CNRS and examined in the University there. He represented the Division at the EEC meeting on 'Soil Protection in the European Community' in Berlin. S. P. McGrath presented a paper at the 20th Trace Substances in Environmental Health Conference at University of Missouri-Columbia, and served as an expert on the Plant Bioassay Committee for the US Army Corps of Engineers in Vicksburg, USA. M. J. Goss visited INRA in Colmar, France, to study different methods for measuring root growth in the field and went to Portugal, funded by the British Council Treaty of Windsor Award. He also gave lectures, funded by the British Council, at the Maize Research Institute in Belgrade, Yugoslavia, and attended a meeting of the Working Group of Cultivations of the EEC Agrimed Programme in Padua, Italy. The following also presented papers, P. C. Brookes at the 4th International Symposium on Microbial Ecology in Ljubljana, Yugoslavia; R. A. Leigh at the NATO Advanced Research Workshop on Plant Vacuoles in Sophia-Antipolis, France; I. G. Wood at the 10th European Crystallographic Meeting in Wrocław, Poland, together with a lecture at the Jagiellonian University in Kraków. A. P. Whitmore visited the Institute for Soil Fertility at Haren in the Netherlands and presented a paper on modelling the nitrogen uptake of winter wheat and G. Brown lectured at the Soil Science Society of America's Golden Anniversary meeting in New Orleans, USA.

H. Jones, Caroline Perry and C. J. P. Shipway were awarded Ph.Ds by the Universities of Wales, Southampton and Cranfield Institute of Technology respectively. I. G. Wood was re-elected to an Honorary Research Assistantship in the Deparment of Geological Sciences, University College, London, and to membership of the Committee of the British Crystallographic Association's Industrial Group. C. C. Biddappa of Central Plantation Crops Research Institute, Kerala, India, returned home having completed four months here and V. A. Banjoko returned to University of Ife, Nigeria, having spent nine months with us. Jedidah R. Onchere of Egerton College, Kenya, completed her work on potassium exchange and E. D. Vance returned to the University of Missouri, USA, having completed two years on a Fulbright-Hays Scholarship. We welcomed Rosenani Abu Bakar from the Universiti Pertanian, Malaysia, to work in the Department for three years, K. Inubushi from the University of Tokyo, Japan, to work for one year on the effects of waterlogging on the soil microbial biomass, and I. M. Buraymah of the University of Khartoum, Sudan, who spent three months here analysing data from a soil survey in that country. P. Alldis and G. Williams departed in October, each having spent three months at the Faringdon site. Orpah Farrington, B. A. Powell, and B. M. Smallfield all continued their studies.

A. J. Pope was registered for a Ph.D. at York University, and L. J. Clarke was awarded one of the first Lawes Trust Studentships and began studies for a Ph.D. R. J. Milling commenced his studies, the first year of which will be spent at Rothamsted, as a SERC/CASE student in collaboration with Southampton University.

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