ROTHAMSTED RESEARCH

Rothamsted Experimental Station Report for 1987

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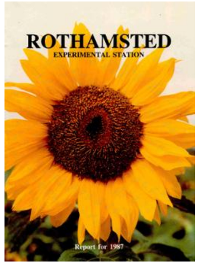

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INTRODUCTION

This is the first report of the recently formed Soils and Crop Production Division of IACR which will consist of the Soils Department and Crop Production Department. The former Soil Microbiology, Soils and Plant Nutrition and Physiology and Environmental Physics Departments and Field Experiments Section have been subsumed in this new Division but these are losses of names only. As far as possible, existing research programmes, established over the last few years, will continue and joint enterprises with other departments, especially Biochemistry, will be strengthened. These new arrangements offer exciting research prospects because all aspects of the soil-plant system can now be studied within one Division. Research in soil fertility will be linked to whole crop physiology through studies on crop nutrition and on mechanisms controlling nutrient uptake and redistribution by crops. The effects of soil microbial populations and soil physical factors on soil fertility and on root activity will be studied alongside interactions between crop nutrition and other agronomic factors affecting crop growth. The expertise of the Farms will be linked more closely with the agronomy research.

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The Working Party for Field Experiments and its five commodity groups and three sub-committees will continue to be the focus for planning and coordination of the field experimental programme. Through this working party and a similar one at Long Ashton Research Station the field programmes at the two major sites will be more closely integrated–to the benefit of both–and to this end both committees have gained joint members during the year. At Rothamsted there were 25 indoor meetings and 17 tours of the field experiments.

Until the latter part of the year research programmes were undertaken in the old departments. However, because there was already much cooperation between various groups which are now within the Division current work is presented here partly by topics.

Research on the efficient use of nitrogen continues–more than half the AFRC's expenditure in the Soil Science Commission goes on this topic. Particular emphasis is placed on the sources of nitrate at risk to loss by leaching from arable soils because such nitrate can find its way into water resources. A review of all our experimental results clearly shows that only small amounts of nitrate remain in soil immediately after harvest. The nitrate which appears during the next six to eight weeks comes from the mineralization of organic nitrogen compounds. Although the nitrate levels in soil following oilseed rape are larger than after cereals, most of this extra nitrate also comes from organic N probably because the microbial decomposition of rape residues releases nitrate quickly. Other data clearly indicate that mineralization of organic residues from leys, farmyard manure and other bulky organic materials can produce very large amounts of nitrate in autumn, in excess of 200 kg N ha^{-1}. Much of this nitrate is at risk to loss by leaching because the nitrogen demand even of early-sown autumn cereals is comparatively small. Work on modelling nitrogen turnover to predict the timing and amounts of nitrate released by mineralization continues, in part supported by a Home-Grown Cereals Authority grant. Reliable and reproducible techniques for measuring denitrification in all types of soil and the leaching of nitrate on freely draining soils are being sought so that full nitrogen balances can be made.

The relationship between nitrogen nutrition and protein quality features strongly in plant physiological studies on winter wheat where modelling also relates to yield prediction. At the whole-crop level there is now a major physiological input to both winter wheat and oilseed rape and continuing support for work at Broom's Barn on the sugar beet crop.

In the presence of heavy metals it appears possible that natural selection processes have favoured a small population of *Rhizobium* which differs from that found on adjoining uncontaminated soils. This is being tested in glasshouse experiments and analysis of the plasmids seeks to differentiate between the strains found on the two soils. This year saw the start of the first field experiment to assess the risk of genetically manipulated *Rhizobium* released into soil transferring genes to native rhizobia. So far no transfer of marked genes has been observed. Work has continued on inoculation techniques and the Agricultural Genetics Company Ltd are sponsoring a new programme to evaluate the possibility of producing vesicular-arbuscular mycorrhizal inoculants.

Work in the Division interacts with two aspects of that in Plant Pathology. Air-borne spore disposal of *Pyrenopeziza brassicae*, the cause of light leaf spot of oilseed rape, is dependent not only on rainfall but on the crop remaining wet for two or three days after rain. The effect of take-all on nutrient uptake by winter wheat is also being studied. Work on the nutrient demand of crops shows that in most moist, arable soils of reasonable depth, diffusive supply will provide sufficient nutrients to the roots, hence if roots are damaged by disease we wish to know the penalty this entails.

Analyses of the 5700 soils in the National Soils Inventory for their total trace element content is now almost complete and the task of processing the data has started. Work on other nutrients, except N, has declined except for a joint project with the Forestry Commission and Institute

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of Terrestrial Ecology using Rothamsted techniques to assess K availability over long periods in situations where it would be uneconomic to apply K fertilizer.

The total number of plots at Rothamsted and Woburn was 10 286, an increase on last year of 2813 partly because two new experiments each had 1140 plots of individually harvested potato plants. The Farms managed 4498 plots with yields taken from 4299, the small-plot staff managed 895 with yields taken from 839; on the remainder the work was divided between Farms, small-plot staff and scientific departments. The effects of the season on the farming operations and the yields of the crops (see p. 127) highlight some of the problems with which the farm management and staff had to cope during the 1986-7 season.

Again and with even more regret it is necessary to report the continued loss of posts as core funding fails to keep pace with the escalating costs of research. A victim of declining funding has been the research programme at Saxmundham (*Rothamsted Report for 1986*, 265). The site has been put down to grass to preserve its valuable set of soils which have received known, and in many cases cumulative, fertilizer treatments since 1899.

SOILS DEPARTMENT

General soil microbiology

Crop inoculation with *Pseudomonas*. Progress was made in screening the collection of *Pseudomonas* (*Rothamsted Report for 1986*, 140) for stimulation of the growth of wheat against the challenge of take-all infection. A small percentage of the bacteria which were screened increased the size of the plants relative to the weights of the uninfected controls. (Macdonald)

Soil actinomycetes. Over 1000 pure cultures were isolated by selective methods designed to obtain four genera (*Micromonospora, Streptoverticillium, Nocardia* and *Actinomadura*) from a collection of air-dried soils of worldwide origin. These genera are candidates for possible commercial exploitation and the cultures are now available; this work was supported by the British Technology Group. Over 20 of the isolates formed a homogeneous group, being distinct from described actinomycetes in their hyphal and colonial morphologies. It is possible that these are members of an undescribed genus and they are being analysed chemotaxonomically. (Macdonald and McLeod with Lacey, Plant Pathology)

Fungal decay of straw. Lignin contributes less than 15% of the weight of straw but protects about 80% of the other components (cellulose and hemicelluloses) from decay. Basidiomycetes have been identified as major agents of straw lignin decay in the soil where they are thought to grow in mixed communities with cellulose-decomposing fungi. Little is known of the distribution and identity of basidiomycetes in arable soils. However, a selective growth medium has been developed which would allow the distribution of basidiomycetes to be determined. The importance of basidiomycetes has been demonstrated in field trials where straw, which was inoculated with these fungi in autumn, decayed more rapidly the following spring and summer. (Bowen and Harper)

Variations in straw decay rate. There have been few reports of the extent to which variation in straw properties can affect decay. Significant differences in decay rate were not detected between cultivars of winter wheat. There were major differences, however, in decay rates between the various anatomical fractions of straw. Leaf blades decayed more than three times faster than stem bases, with other plant parts intermediate. (Harper)

Vesicular-arbuscular mycorrhiza (VAM) fungi

Susceptibility of roots to mycorrhizal infection. Clover roots become immune to infection by *Glomus mosseae* when less than five days old whereas leek roots retain their susceptibility

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for at least 32 days (Hepper, *New Phytologist* (1985) **101** , 685-693). It has now been shown that the period of susceptibility, during which a root can be infected, is dependent on the fungal species being tested. (Rolfo, Grace and Hepper)

Biochemical characterization of VAM fungi. Isoelectric focusing on ultra-thin gels has been shown to be a very sensitive technique for characterizing different species of mycorrhizal fungi by their total protein patterns. Diagnostic patterns were obtained by silver staining using extracts derived from as few as five spores. (Hepper with Robinson, Entomology and Nematology)

Quantification of mycorrhizal infection. VAM fungi can be identified on the basis of the mobility of diagnostic fungal enzyme bands during gel electrophoresis of infected root extracts (Hepper *et al.*, *New Phytologist* (1986) **102** , 529-539). The intensity of the staining of the bands in the gel is proportional to the amount of mycorrhizal infection in the root sample, thereby offering a method of quantifying individual fungi present in multiple infections especially when fungi are anatomically similar. (Hepper; Rosendahl, Sen, Azcon-Aguilar and Gostick)

Stimulation of VAM fungal growth by sulphur-containing compounds. Dithiothreitol (DTT) (2,3 dihydroxy-1, 4 dithiolbutane) stimulates hyphal growth of *Glomus caledonium* in agar at 1–20 mg S l^{-1}, although the enhancement is less than that observed with sulphur-containing inorganic compounds such as potassium sulphite. A synergistic effect was seen when DTT and cysteine were supplied together in the medium. (Hepper and Azcon- Aguilar)

Amelioration of Mn toxicity. Mung bean (*Vigna radiata*) grown on partly sterilized (γ-irradiated) soil, pH 7.5, showed severe symptoms of manganese toxicity but, when infected by vesicular-arbuscular mycorrhizal fungi grew normally. The reason for this amelioration of Mn toxicity is not known but could not be attributed to improved P nutrition of mycorrhizal plants. (Stribley and Grace, with Dr. R. Vencatasamy, visiting worker)

Microbial genetics

***Rhizobium*–symbiotic genes.** The symbiotic genes located on the Sym plasmid of most *Rhizobium* strains appear to control the development of nitrogen fixing root nodules sequentially from host recognition to expression of the nitrogenase enzyme. Recently, a cluster of *fix* genes in *R. meliloti* that is essential for later stages in this development have been identified and can be regarded as having three sections: two groups of unique genes separated by a group of genes some of which are reiterated elsewhere on the Sym plasmid (David *et al.*, *Journal of Bacteriology* (1987) **169**, 2239-2244). Both DNA homology and functional complementation of these Sym plasmids with those of *R. leguminosarum* bv. *viceae* have been investigated. One of the unique groups of genes shows homology to Sym plasmid DNA in *R. leguminosarum* bv. *viceae* strains JI248 and JI300. Interestingly, a *R. meliloti* mutant defective in one of the genes regained the ability to fix N_2 in root nodules when Sym plasmids from either of these strains was transferred into it. However, it was not possible to complement a mutant defective in one of the unique genes of the second region by either Sym plasmid: a gene probe containing this region showed DNA homology to the Sym plasmid in JI300 but apparently not to any part of the genome of JI248. Future experiments should establish which of these genes are essential for N_2 fixation in rhizobia other than *R. meliloti*. (Snellgrove and Hirsch; White and Latham with Dr. P. Boistard INRA, Toulouse)

Release of genetically manipulated rhizobia. Rhizobia are ubiquitous soil bacteria which have been well studied in the laboratory and it is likely that strains improved by genetic

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manipulation and intended for agricultural use will be produced in the near future. Unlike other soil microbes, rhizobia can be sampled easily via the root nodules they induce on the host plant. They are, therefore, an ideal model soil microorganism for experiments to investigate the occurrence of gene transfer in the environment. Gene transfer can be followed using transposons like Tn*5*, which determines resistance to kanamycin (Kan^R) and neomycin (Neo^R) (and in some bacterial strains also to streptomycin) and it has a DNA sequence that is easy to detect using labelled homologous probes. Tn*5* can insert at random into DNA in a wide range of Gram-negative bacteria and when transposed into DNA of a new host it may be stably maintained, even when the plasmid that carried it into the new host is itself unstable and is lost. It is, therefore, a very convenient marker gene that can be used to monitor genetic interactions (*Rothamsted Report for 1986*, 143). In the laboratory, the conjugative Sym plasmid of a *R. leguminosarum* bv. *viceae* strain with chromosomally-located mutations to resistance for the antibiotics streptomycin and rifampicin (Str^R, Rif^R) was marked by a Tn*5* insertion that did not appear to disrupt any identifiable genes. The marked strain was then used in a field experiment as a pea inoculant. Because Tn*5* was originally isolated from a naturally occurring *Klebsiella*, the *Rhizobium* strain is classed as an interspecific hybrid and the release took place only after the Advisory Committee for Genetic Manipulation, the relevant committee of the Health and Safety Executive had discussed the experiment and decided that it had no objection.

Peas inoculated with the marked strains were sown on a 100 m^2 plot at Rothamsted and tops and roots harvested sequentially. Inoculation provided about $3x10^4$ rhizobia per g soil, which was higher than the numbers of the indigenous *R. leguminosarum* bv. *viceae* population in the field. However, the inoculant was found to be at a competitive disadvantage and only 7% of nodules tested 17 weeks after planting contained the inoculant strain. So far rhizobia have been isolated from over 1000 pea root nodules and these are still being checked for the presence of the Kan^R Neo^R and DNA homology markers of Tn*5* in the absence of the Rif^R Str^R markers of the inoculant. Finding such strains would indicate that genetic interaction between introduced and native rhizobia had occurred. In the following years populations of *R. leguminosarum* bv. *trifolii* and bv. *phaseoli* as well as *R. leguminosarum* bv. *viceae* will be screened for the presence of Tn*5*, after the relevant host plants have been grown in the field. The results will provide invaluable data for assessment of the risk of gene transfer between more radically altered rhizobia and native strains in the future. (Spokes and Hirsch; Latham and White)

A molecular approach to the ecology of soil microorganisms. The experiment described above, which involved the release of genetically-marked rhizobia in the field, is providing material to develop new methods of screening soil microbial biomass for the presence of a specific DNA sequence, Tn*5*. The procedure should allow the frequency of the Tn*5* genome in the soil microbial gene pool to be measured. Evaluation of this frequency will allow prediction of the likely consequences of releasing the marked bacterium. (Hirsch and Macdonald)

VAM fungi. Development of methods to improve DNA extraction from VAM fungi has continued and DNA homology between a ^{32}P-labelled probe containing ribosomal RNA genes from *Mucor racemosus* and total DNA extracted from several different species of VAM fungi has been demonstrated. The limited amount of VAM material which can be purified from pot cultures of mycorrhizal plants has impeded the progress of the project. However, we have recently been able to extract DNA from pure axenic cultures of *Endogone pisiformis*, a non-mycorrhizal relative of the VAM fungi which is classified in the same family, the Endogonaceae. This should allow us to obtain sufficient DNA to

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construct a gene library which will be an invaluable aid to future studies on the VAM fungi. (Hirsch; Gibson)

Inoculants and crop inoculation

Techniques. Methods used to inoculate leguminous seed must provide sufficient viable rhizobia to ensure adequate nodulation of the host plant.

On-farm methods. These often involve mixing dry or moistened seed with peat based inoculants immediately prior to sowing, but because of weak adherence and poor rhizobial survival, there is no certainty of nodulation. Larger quantities of inoculant can be attached to seed by the use of an adhesive (40% gum arabic, 5% methyl cellulose) which also promotes rhizobial survival on the seed surface. An adhesive which leads to a two- to threefold increase in retention of the inoculant applied by dry dusting and which could be added to the carrier material during inoculant production was reported previously (*Rothamsted Report for 1986*, 144). Subsequently this type of inoculant formulation has been shown to provide high rhizobial numbers on large legume seeds. This methodology has been extended to *Pseudomonas* spp. (and other plant growth promoting rhizobacteria) to provide inoculants with a shelf life in excess of one year.

Inoculant manufacturers recommend that seeds should be planted within 2–24 h of inoculation because of the high rhizobial mortality on the surface of inoculated seed. A copolymer has been identified and incorporated into an on-farm inoculation package which allows farmers to inoculate their seed up to one month before sowing; lucerne seed for example maintained in excess of 10^4 viable rhizobial cells per seed during this time. (Williams and Day, with Jeavons)

Pre-inoculated seed. Pre-inoculation of legume seed involves the incorporation of a *Rhizobium* inoculant into one or more of a multi- layered coating material. The commercial process usually requires a drying phase at temperatures that are deleterious to *Rhizobium* survival, therefore commercial products have been unreliable. Recently, work has been carried out on mixtures of peat, clays and various protectants which support high *Rhizobium* numbers on the seed surface and a pre-inoculation technique has been developed that requires no high temperature drying. The method provides $>10^5$ and $>10^3$ viable *Rhizobium* cells per seed on large and small legume seed respectively. The pre-inoculated seed has a shelf life of more than three months. A patent application has been filed by the Agricultural Genetics Company (AGC) to protect this discovery. (Williams and Day, with Jeavons)

Granular inoculants. Granular inoculants are used when legume seed is dressed with fungicides that are toxic to *Rhizobium*. The granules are normally combine-drilled with the seed or may be broadcast pre-sowing. Formulations and granulation methods have been developed which provide $>10^8$ viable *Rhizobium* cells g^{-1} and a shelf life of at least seven months. Such granules have been field tested in Italy, France (soya) and the UK (*phaseolus*) and resulted in well nodulated plants. Minor problems because of bridging of the granules in the applicator have occurred and improved flow characteristics and extended shelf life are being sought. New Plant Products Laboratories (NPPL) are marketing the granules for soya beans and the AGC have filed a patent to protect the granulation method. (Williams and Day, with Jeavons)

VAM inoculants. VAM inoculants are not currently produced commercially in the UK. The AGC have funded work to develop an *in vivo* system with a view to commercial production.Tropical and sub-tropical host plants are being grown in mixed granular porous substrates and irrigated with low phosphate nutrient solutions. As the host plant matures the porous substrate becomes heavily infected with VAM mycelium and spores. This material

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can be used as an inoculant after removal of plant debris and drying. Future work will study the shelf-life characteristics of the product, develop quality control procedures and examine the efficacy and commercial value of the inoculants in trials with commercial growers. (Arias, Rolfo and Day)

Dual inoculation. Large multi-pellets (2 cm × 1 cm) developed for use as mycorrhizal inoculants were tested for clover seed germination and VAM inoculum infectivity after storage for one year at 7°C in polythene bags. When compared to freshly made pellets there was no reduction in either germination or infectivity. Smaller multi-pellets (0.5 cm × 0.3 cm) which had been kept at room temperature for two years showed no drop in infectivity of the VA mycorrhizal inoculum during storage. (Grace, Sainz, Honrubia, Hayman)

Soil organic matter and biomass

Biomass measurements as an 'early warning' of changing soil organic matter levels. Biomass C, N, adenosine 5′-triphosphate (ATP), soil organic C and N were measured in selected grassland, arable and fallow soils from Rothamsted and Woburn. The ratios [biomass C]/[total soil organic C] and [ATP]/[total soil organic C] were significantly higher in grassland and arable soils receiving inorganic fertilizers or farmyard manure (FYM) than in fallow soils or in soils in an alternate crop/fallow rotation. However, [biomass C]/[biomass N] and [ATP]/[biomass C] ratios were very similar in all the soils. These results support previous findings that changes in the ratio [biomass C]/[total soil organic C] provide an early and sensitive indicator of changing soil C inputs, changes which often cannot be detected from soil organic C measurements alone. (Wu, Brookes and Jenkinson)

Fumigation-extraction techniques for measuring microbial biomass. A fumigation-extraction (FE) technique for measuring soil microbial biomass has been developed (*Rothamsted Report for 1986*, 150-151). It gave biomass values which agreed closely with those measured by the standard fumigation-incubation method (FI) (Jenkinson & Powlson, *Soil Biology and Biochemistry* (1976) **8**, 209-213) in unamended, preincubated soils. In both methods the cells of the soil biomass are lysed with $CHCl_3$. In the FE method, the microbial material thus released is extracted with 0.5M K_2SO_4 and measured as extractable organic C or N, whereas in the FI method, the material released is allowed to decompose and the *extra* CO_2 or mineral N liberated measured.

Using the FE method, soil biomass C and N can now be measured in soils immediately after sampling, during prolonged periods of anaerobic incubation and in soils containing large amounts of actively decomposing straw–all conditions where the original FI method is unreliable. (Brookes and Jenkinson)

Biomass measurements in soils containing decomposing straw residues. Straw (2% by weight) was added to both a sandy and a clay soil and incubated for 13 or 35 days. As expected, measurements of biomass C and N by the fumigation-incubation method (FI) were unreliable. In contrast, biomass C and N measured by fumigation-extraction (FE) were closely correlated, with a mean biomass C/N ratio of about 6, a similar C/N ratio to that in unamended soils. Changes in soil ATP content and α-amino N (i.e. ninhydrin-reactive N), proposed by Amato and Ladd (*Soil Biology and Biochemistry* (1988) **20**, 98-106) as a useful index of biomass, both correlated closely with biomass C and N measured by FE in straw-amended soils. (Ocio, Brookes and Jenkinson)

Biomass measurements in waterlogged soils. Changes in biomass C and N, ATP and adenylate energy charge (AEC) were measured and compared in Rothamsted soils and in Japanese paddy soils during aerobic and anaerobic (waterlogged) laboratory incubations.

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Biomass C and N, measured by fumigation-extraction (FE) declined little, if at all, during aerobic and anaerobic incubations lasting 80 days. α-amino N, (see above) was also a good indicator of biomass when these soils were incubated aerobically but did not give meaningful results in anaerobic soils, perhaps because NH_4-N accumulated under anaerobic conditions.

Total soil adenine nucleotide content (A_T = [ATP] + [ADP] + [AMP]) also remained reasonably constant during both aerobic and anaerobic incubations of a Rothamsted grassland soil and a Japanese organically-manured soil. However, adenylate energy charge AEC = ([ATP] + 0.5[ADP])/([ATP] + [ADP] + [AMP]), decreased in both soils during an 80 day anerobic incubation, from about 0.75 in the fresh soils to about 0.55 in the Japanese and 0.3 in the Rothamsted soils respectively. When the anaerobically incubated soils were reoxygenated, the AEC in the Japanese soil returned to near the level in the fresh soil, but not in the Rothamsted soil. (Inubushi, Brookes and Jenkinson)

The use of a control in determining biomass C by fumigation-incubation (FI) and fumigation-extraction (FE). In measuring biomass C by FE the amount of non-biomass soil organic C extracted by K_2SO_4 can be unambiguously measured in non-fumigated soil extracts and this amount (the control) is subtracted from organic C extracted from fumigated soil extracts to give a measure of microbial C. With FI the exact value of the control, i.e. the amount of non-biomass soil organic C mineralized to CO_2-C in fumigated soil, is more controversial. In soils ranging from about pH 5 to 8, we take the control to be equal to the organic C or N mineralized in non-fumigated soil over the same period. This has now been tested directly following ^{14}C-labelling of soil biomasses by incubating soils with ^{14}C-glucose for long periods. If the assumptions underlying the FI and FE methods for measuring soil biomass C are correct, the specific activities measured by both methods should be identical. In fact they were *remarkably* close which means that basal respiration proceeded at similar rates in fumigated and non-fumigated soils, supporting the use of a non-fumigated control in FI measurements of biomass C in soils over this pH range. In more acid soils fumigation reduces basal respiration and a control is not used in FI. (Vance *et al.*, *Soil Biology and Biochemistry* (1987) **6**, 697-702). (Wu, Brookes and Jenkinson)

Soil nitrogen and nitrogen fertilizer need

The effects of increasing length of ley on the growth and yield of winter wheat. For many years yields of cereals on the Intensive Cereals experiment at Woburn were small and neither additional fertilizer nor soil sterilants increased them. It was speculated that the soil might contain too little organic matter for the crops to attain their full potential. From 1981 a new grass-clover ley was established each year for six years, and all were ploughed out and sown to winter wheat cv. Mercia in 1986.

The NO_3-N content of the soil in October ranged from 93 after one year ley to 229 kg NO_3-N ha^{-1} after six years; only one- and two-year leys had less than 200 kg NO_3-N ha^{-1}. By November soil NO_3-N had declined and ranged from 42 to 155 kg NO_3-N ha^{-1}. Between October and November there was a large decline in NO_3-N in surface soils which was compensated for in part by an increase in the 60-90 cm horizon as nitrate moved down the profile. By February little nitrate remained, ranging from 11 to 34 kg; by April the range was only 5 to 8 kg NO_3-N ha^{-1} to 90 cm.

Growth was measured on plots without spring N. In early January dry matter yield ranged from 65 to 99 g m^{-2}, increasing with length of preceding ley up to five years. The same pattern was repeated at the end of January and in mid-May with ranges of 123 to 221, and 287 to 663 g m^{-2} respectively. By anthesis, in mid-June, dry matter yield of wheat after one or two year leys was smaller (594 and 675 g m^{-2}) than in the three to six year group (966 to 1107 g m^{-2}).

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At harvest, grain yield obtained from soil N alone was 4.86, 5.82, 7.72, 8.37, 8.37 and 8.24 t ha^{-1} following leys of one to six years duration. The mean yield from all plots was 8.48 t ha^{-1} and maximum yield was given by a spring application of 250, 200, 150, 150, 100 and 50 kg N ha^{-1} after leys of one to six years respectively. (Darby, Hewitt, Penny, Johnston and McEwen)

Recovery of organic N by crops. The long-term effects of nitrogen fertilizers on the reserves of organic N in the soil have been assessed in the Broadbalk continuous wheat experiment on plots normally given between 0 and 192 kg N ha^{-1} per year. Yields on subplots given no fertilizer N in 1987, ranged from 1.44 to 3.22 t ha^{-1} of grain (85% DM) after no N and 192 kg N ha^{-1} per year respectively. Each no-N subplot in 1987 produced approximately 50% less grain than the equivalent plot given N at the usual N rate. Thus the amount of N made available in 1987 depended on the level of N in previous years. (Glendining, Poulton and Powlson; McCann, Fry and Riley)

Efficient use of nitrogen

Leaching of nitrate from arable land. The current debate on why nitrate levels are increasing in aquifers has focussed attention on the fate of nitrogen from fertilizers applied to arable crops. Although some nitrate can be leached soon after application in spring, the main leaching losses occur during late autumn and winter and it is often assumed that this nitrate has come from fertilizer applied in spring. We have tested this by applying ^{15}N-labelled fertilizers, supplying 47 to 234 kg N ha^{-1}, to winter wheat growing in three different soil types over the last seven years. Between 7% and 36% of the fertilizer N remained in the topsoil at harvest, but it was almost entirely in *organic* forms including roots, microbial biomass and stabilized organic matter; only 1-4% of the applied fertilizer N was present as nitrate. On average, this fertilizer-derived inorganic N represented less than 10% of the total inorganic N in the soils at this time; the remainder came from the mineralization of soil organic matter. Even with oilseed rape given 257 kg N ha^{-1} as fertilizer, only 4% of the applied N remained as nitrate at harvest.

The influence of long-term cropping history. Cropping history has a major influence on amounts of organic matter which can be mineralized and hence, on nitrate leaching risk. This is illustrated by results from the Ley-Arable experiment on a sandy loam soil (Cottenham Series) at Woburn. Winter wheat was grown in either an all-arable rotation or following leys; after harvest the soil (0–50 cm) contained 15–20 kg and 50–65 kg NO_3-N ha^{-1} respectively. The length of ley (three or eight years) or its type (grass given N fertilizer or grass with clover) had no effect. Of the NO_3-N present, less than 5 kg ha^{-1}was from the current year's ^{15}N-labelled fertilizer and this also was unaffected by past cropping. (Macdonald, Powlson, Poulton and Jenkinson; Fry, Voice and Chaplin)

The influence of organic manuring. It is sometimes suggested that the amounts of nitrate leached from arable land would be decreased by using organic rather than inorganic nitrogen fertilizer. During the winter of 1986-87 two soils, one given 35 t ha^{-1} farmyard manure the other NPK fertilizers for the last 150 years, were sampled for nitrate to a depth of 110 cm on ten occasions. On each sampling occasion, soil from the plot receiving FYM contained at least 70 kg ha^{-1} *more* inorganic N (mainly nitrate) than soil from the plot receiving inorganic fertilizers. Long-continued organic manuring had led to increased exposure of nitrate to leaching. (Poulton, Powlson and McCann)

Influence of drainage and cultivation. Because we can monitor drainage accurately in the Brimstone experiment (see p. 108), nitrate losses can be assessed and related to both

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drainage and cultivation treatment. In the drained land about 90% of the NO_3-N lost by leaching moves from the soil into ditches through the mole and pipe drain system. The effects of tillage on these losses have been measured under three autumn sown crops, oilseed rape, 1984-5; winter wheat, 1985-6; oats, 1986-7. In October 1984 46 kg N ha^{-1} applied to the oilseed rape was followed by a top-dressing of 239 kg N ha^{-1} in March. A total of 48.7 kg N ha^{-1} was lost from the ploughed soil of which 41 kg was lost over winter before the spring top-dressing. The loss from the direct-drilled soil was 40 kg N ha^{-1} with only 27 kg being leached over winter. Although no seedbed N was applied to the following winter wheat, over-winter losses were considerable, averaging 48.3 kg N ha^{-1}. At the end of April 1986 130 kg N ha^{-1} was applied. There was no rain for four days and only 8.5 mm in the next ten days, so leaching losses were expected to be small and totalled only 0.5 kg ha^{-1}. Again in autumn 1986 no nitrogen was applied to the oats and losses averaged 30 kg N ha^{-1} with 5 kg ha^{-1} more being lost from ploughed soil than from direct-drilled soil.

Computer programs have been written to integrate drainflow and nitrate concentrations over time to improve the calculation of nitrate leaching losses and speed the transfer of data between Rothamsted and the Field Drainage Experimental Unit at Cambridge. (Goss, Howse with Lane, Statistics and Mr G.L. Harris, Field Drainage Experimental Unit, and Dr P. Colbourn, Welsh Plant Breeeding Station)

Long-term nitrate leakage from soils. Early data from the Rothamsted Drain Gauges (Miller, *Journal of Agricultural Science, Cambridge* (1906) **1**, 377-399) have been used to determine the likely time-scale for the uncontrollable leakage of nitrate from soils. The Drain Gauges contain blocks of soil, previously in arable cultivation, that have remained uncropped, unmanured and uncultivated, save for hand-weeding, since 1870. At the start the soil contained 0.154%N in the top 25 cm and this organic matter has mineralized slowly. During 1877–1883 the average annual loss of nitrate was 45 kg N ha^{-1} per year. This is very similar to the amount alleged to be leaching to aquifers on a national scale from fully fertilized winter wheat crops (Foster *et al.*, *Philosophical Transactions of the Royal Society* (1982) **B296**, 477-489). Calculations, which removed the effects of the large fluctuations in annual rainfall, suggest that it would have taken 40 years before the annual nitrate loss was halved. (Addiscott; Bailey)

Losses of nitrogen fertilizer by denitrification and leaching. The two major problems in measuring denitrification losses accurately by acetylene inhibition are (i) the large spatial and temporal variability of the process and the resultant difficulty in obtaining a realistic mean value without excessive labour, and (ii) the slowness of diffusion of acetylene into and N_2O out from the very soils on which the amount of denitrification is expected to be large. Techniques using cover boxes and coring have been compared. The former decreases errors from (i) but increases problem (ii); the importance of the problems are reversed with the coring technique. No one method is ideal for all conditions. Both methods have been used, in conjunction with ^{15}N balance experiments, to study the efficiency of N fertilizer applied in spring to winter wheat grown on the sandy, silty clay loam, and clay soils at Rothamsted, Woburn and Brimstone. Although denitrification losses at Rothamsted during autumn and winter 1987 were as large as 2 kg N ha^{-1} per day after the unusually heavy rain in October, total losses so far are only 29 kg N ha^{-1} on a plot heavily manured with FYM each year and 5 kg N ha^{-1} on a plot given N fertilizers. No FYM, but 25 kg N ha^{-1} labelled with ^{15}N was given to both plots in autumn before measurements started. (C.P. Webster and Goulding)

Fate of nitrogen in residues from oilseed rape. In the 1985 multi-disciplinary rape experiment, ^{15}N-labelled fertilizer ($^{15}NH_4{}^{15}NO_3$ at 257 kg N ha^{-1}) was applied to early-sown rape in March. At final harvest, in July, 63 kg ha^{-1} of this N was left in roots, leaf litter,

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stubble and soil; the latter included 10 kg ha^{-1} of NO_3-N. Winter wheat followed the rape and, at harvest in 1986, the wheat had taken up 22% of the residual N, 42% remained in soil and 36% was unaccounted for. The proportion of residual N unaccounted for is larger than previously found for ^{15}N-labelled residues of N applied to wheat, when only about 10% was lost during the following year. Two factors probably contributed to this difference. First, a somewhat larger proportion of the residual fertilizer N left in soil after rape is in the nitrate form, though the absolute quantity is not large. Second, rape residues appear to have a narrower C/N ratio than those of wheat. Thus it is likely that inorganic nitrogen will be released as soon as the rape residues start to decompose, leaving nitrate at risk to winter leaching. The decomposition of wheat residues immobilizes some nitrogen in autumn, diminishing the amount of nitrate in soil. (Powlson, Poulton and Jenkinson; McCann)

The immobilization of fertilizer N. Last year we reported (*Rothamsted Report for 1986*, 149-150) the disappearance of mineral N from the soil profile between March and May in a field experiment. We suggested that N was immobilized by soil microorganisms as they used plant-derived carbon for microbial synthesis. This hypothesis was tested by growing spring wheat in pots of surface soil taken from the same field. For the first 48 days N supply was limited to ensure that the crop and the biomass would actively compete for N added as either $^{15}NH_4NO_3$ or $NH_4{}^{15}NO_3$ equivalent to 150 kg N ha^{-1}. At intervals over the next 85 days both crop and soil were sampled and analysed for total and ^{15}N. By final harvest about 12% of the $^{15}NO_3$-N was immobilized in the soil, 78% was in the crop and part of the remainder was lost, probably by denitrification. Similarly, about 7% of the $^{15}NH_4$-N was immobilized in the soil, 70% was in the crop, 14% fixed in the clay and the rest lost. Thus some ^{15}N was immobilized, but less than anticipated and probably too little to seriously limit crop growth. (Weir, Brookes and Barraclough)

Monitoring nutrients and pollutants in rain, drainage and borehole waters.

Rothamsted monitors nutrients and pollutants in rain, drainage and borehole waters to assess the importance of changes in both. Recent data show a decreasing concentration of SO_4-S, NH_4-N and NO_3-N in precipitation at Rothamsted, Woburn, Broom's Barn and Saxmundham over the last few years. This agrees in part with national data from the Warren Spring Network (*Rothamsted Report for 1986*, 156) which noted that H^+ and non-marine SO_4-S in rain decreased during the periods 1978–80 and 1981–5, and also with national decreases in SO_2 emissions. Such results indicate the need for work on S inputs to crops.

The mean yearly concentration of NO_3-N in the groundwater samples from all the boreholes on Rothamsted Farm and at Broom's Barn is below the WHO and EEC recommended limit of 11.3 mg NO_3-N l^{-1}. The concentrations found in the individual boreholes and the trends in those concentrations seem to be related to ground cover, slope, soil type and depth of soil overlying the chalk, and depth of the water table below the surface. Concentrations are lowest ($\sim$5.7 mg NO_3-N l^{-1}) and decreasing in the groundwater 45 m below an area of mixed grass and arable cropping on Highfield at Rothamsted, where the soil covering the chalk is $\sim$5 m flinty silt loam and boulder clay. Concentrations are greatest ($\sim$9.3 mg l^{-1}) in the groundwater of Broom's Barn borehole, $\sim$40 m below the surface and with 11 m sand and gravel over chalk. Concentrations ($\sim$8.1 mg l^{-1}) are increasing only in the water 15 m below Knott Wood, a sloping site on Rothamsted Farm which has only 1 m clay loam overlying the chalk. Only in the Broom's Barn borehole do the monthly samples occasionally (once a year) rise above 11.3 mg l^{-1}.

In contrast to NO_3-N, little concern has ever been expressed over dangers to health from K. Rather, adequate K is vital to human health and deficiency is more likely to be a problem than excess. However, in 1980 the EEC issued a recommended limit for K in potable waters

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of 10 mg l^{-1} and a maximum of 12 mg l^{-1}. Mains water at Rothamsted (1.3 mg K l^{-1}) and Woburn (3.4 mg K l^{-1}) is well below this. Water at Rothamsted is pumped from chalk under clay, that at Woburn from a sandstone aquifer. These levels and the EEC recommendations are seen in perspective, however, when compared with K concentrations in bottled mineral waters of up to 5 mg l^{-1}, in spa waters of up to 150 mg l^{-1}, in human milk of 600 mg l^{-1} and cow's milk of 1500 mg l^{-1}. (Goulding; Howe)

Modelling soil and crop nitrogen

Modelling of leaching. Work has continued to broaden the applicability of the improved leaching model described in the *Rothamsted Report for 1985* (p.167). The model now has two additional parameters which take account of the soil's capacity to hold water and its permeability. The capacity parameter can be estimated from particle size distributions (PSDs) using equations derived by the Soil Survey and Land Research Centre (Hall, Reeve, Thomasson & Wright (1977) *Water retention, porosity and density of field soils*, Soil Survey Technical Monograph No.9.). The permeability parameter has now been related to the mean percentage of clay. (Addiscott; Bailey)

The leaching model has been put in a user-friendly form and is now in use with ADAS. In its modified form it has been incorporated into the full soil and crop nitrogen model and a user-friendly version of this transferred to ADAS. (Bland)

Implications of soil heterogeneity for leaching. The two main parameters of the leaching model (above) both vary within a site, so that each should properly be represented by the mean and variance of its probability distribution. Taking account of the variances somewhat improved the simulation of leaching at Rothamsted, but not to the extent that serious errors arise from their omission. (Addiscott and Bland)

Predicting the growth and N uptake of winter barley. The simple function describing nitrogen uptake and dry matter accumulation of tops and rooting by winter wheat (*Rothamsted Report for 1984*, 181-184) has been extended to winter barley. As for wheat, it is possible to predict the rate constant, which determines early growth and N uptake, soon after sowing so that the function can be used predictively. (Whitmore and Addiscott; Bailey)

Simulating the growth of continuous winter wheat on Broadbalk. The simple function for describing growth, nitrogen uptake and rooting (*Rothamsted Report for 1984*, 181-182) has now been incorporated with models for estimating the turnover of organic matter in soils and nitrate losses through leaching (*Rothamsted Report for 1986*, 151). This combined model was used to predict the nitrogen taken up by wheat grown continuously on those plots in the Broadbalk experiment which receive 0, 48, 96, 144 or 192 kg N ha^{-1} annually. Once started, the model requires only daily soil temperature, rainfall and evaporation and a measurement of the C/N ratio of straw at harvest and an estimate of the weight of stubble returned to the soil in order to predict the flow of N through the soil for the following season. (Whitmore, Parry, Jenkinson and Addiscott)

Nitrogen leaching and N uptake by crops on viewdata. For the second year we provided information to farmers through the Rothamsted Farming Service on Prestel Farmlink and Agviser (now merged). As last year, the information was in two parts. For each week between January and April we predicted crop uptake, leaching and mineralization and compared our simulations with long-term mean values to tell farmers if their soils and crops were likely to contain much nitrogen above or below the average. On the basis of our predictions ADAS supplied advice on how farmers should respond.

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Between March and June we computed the likely percentage loss of applied nitrogen fertilizer by leaching (below 25 cm and 50 cm depth). This is of particular value to farmers sowing crops in the spring or applying N top dressings to autumn-sown crops. When demonstrated at the Royal Show the system attracted much interest. (Bland, Addiscott and Whitmore with Dr R. Sylvester-Bradley, ADAS Cambridge)

Soil fertility requirements of crops.

Soil solution concentrations and nutrient fluxes. A mechanistic nutrient supply model (Baldwin *et al.*, *Plant and Soil* (1973) **38**, 621-635) has been used to calculate soil solution concentrations needed to sustain nutrient fluxes into high-yielding crops by diffusive supply. This approach allows soil fertility levels to be calculated which take account of the concentration and replenishment of nutrients in soil solution, their transport to roots and the growth of roots.

The model has been applied to winter oilseed rape yielding 5 t ha^{-1} seed. Most nutrient uptake by this crop occurred in April and May and maximum uptakes (in kg ha^{-1}) and uptake rates (in kg ha^{-1} d^{-1}) were; N, 350, 4.2; P, 43, 0.41; K, 300, 2.4; Ca, 290, 3.1; Mg, 16, 0.18. The roots reached a depth of at least 180 cm, but >75% were in the top 20 cm of soil during the main uptake period where maximum rooting density was 10 cm cm^{-3}.

Solution concentration differences between root surfaces and the bulk soil necessary to give adequate diffusive supply of nutrients at the time of maximum fluxes into roots were: 98 μM N, 12 μM P, 23 μM K, 77 μM Ca and 9 μM Mg. Actual bulk soil concentrations were 4500 μM N, 10 μM P, 399 μM K, 2675 μM Ca and 85 μM Mg. Only in the case of P is transport likely to have limited uptake.

The P buffer power of this soil was 58 and, if the critical level of bicarbonate-soluble P in soil is 15 mg l^{-1} for oilseed rape, then this corresponds to 10 μM P in solution (assuming a linear isotherm). This value is very close to the concentration difference calculated above for adequate diffusive supply of P for this high-yielding crop. The results of other similar calculations (*Rothamsted Report for 1986*, 151) indicate that nutrient transport is unlikely to limit uptake by autumn sown crops when these are grown in moist, arable soils with unrestricted root growth, but that uptake by spring crops is much more likely to be limited by nutrient mobility. (Barraclough)

The effects of drought and N-supply on the growth of winter wheat. Experiments on winter wheat testing the effect of drought on differing soil types, and its interaction with N-supply have now been completed for three soil types: a heavy clay soil (Evesham series), a silty clay loam (Batcombe series) and a deep loam (Hook series). These three soils supplied between 90 and 130 mm of stored water to the wheat at full transpiration rates and a further 60 – 100 mm under increasing drought stress. United Kingdom weather records show that average annual rainfall plus these amounts of soil water should be sufficient, without irrigation, to prevent serious losses of yield from drought in healthy winter wheat crops in most years. (Weir and Barraclough; Green and Kent)

Winter rainfall and the yield of winter wheat in Portugal. Wheat yields in Portugal are frequently poor compared with other countries with a similar climate. Preliminary studies showed a significant but negative correlation between winter rainfall and the yield of winter wheat in Portugal, a totally unexpected result for a Mediterranean climate because crops normally depend on stored water.

A more detailed study showed that wheat responded quite differently to winter rainfall on clay soils and coarse textured soils. It was only on coarse textured soils that yield decreased with increasing winter rainfall, whereas on clay soils it increased. Water regimes were monitored during the winter on a coarse textured soil derived from quartz diorite and on

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a clay soil. Although the water-table reached the soil surface for almost two weeks at both sites the wheat yielded well, 4.2 t ha^{-1}, on the clay soil compared with 0.5 t ha^{-1} on the coarse textured soil. This suggests that temporary waterlogging was not the primary cause of poor growth on the coarser textured soil. Laboratory experiments confirmed that crop response to waterlogging was similar in both soils, growth was decreased by up to 25%.

In the field, variation in soil acidity related closely to crop performance and, in addition, on the quartz diorite soil poor growth was associated with soil rich in manganese (but not in aluminium) and poor in calcium and magnesium. When these soils were leached in the laboratory, the pH did not change and dry matter accumulation was related to the manganese concentration in the leaves. Poorest growth was at concentrations exceeding 250 μg Mn g^{-1} (dry weight), a concentration generally considered toxic for wheat. Both addition of lime (6 t ha^{-1}) to increase pH close to 6, and addition of nutrients other than NPK increased growth whether or not the soil had been leached and a combination of both gave the best growth. Magnesium was the nutrient that was deficient.

We have concluded that these coarse textured soils should be limed regularly with dolomitic limestone because seasonal variation in soil pH is a major limitation for correctly diagnosing problems in the field. This work was sponsored by the British Council through the Anglo-Portuguese joint research programme Treaty of Windsor 1986/87. (Goss, with Prof. A.L. Azevedo and Eng. M. Carvalho, University of Evora, Portugal)

Micronutrients in soils and crops

Effects of metals from past sewage applications on N_2 fixation by clover. Decreased yields and nitrogen fixation of clover grown in pots of metal-contaminated sludged soil have been reported previously (*Rothamsted Report for 1986*, 154). Effective fixation, however, occurred with uncontaminated soil from the same field. Investigations of *Rhizobium* strains isolated from effective and ineffective root nodules revealed genetic differences in the bacteria; ineffective strains whilst retaining the ability to form root nodules were unable to fix nitrogen. This was true even in the absence of metals in plant tests performed on agar slopes under axenic conditions. Examination of the plasmids of a number of isolates of effective and ineffective bacteria after gel electrophoresis revealed a heterogeneous pattern of plasmid bands in the former (characteristic of 'normal' populations) and a single pattern in the latter, suggesting that a specialized population has been selected for its survival in metal-contaminated soil. (McGrath and Hirsch, with Dr K.E. Giller, Wye College)

Availability of borate from various fertilizers and borate ores. Laboratory experiments showed that three refined borate fertilizers were completely soluble in water, but that three crude ores were far less soluble, releasing only 10–20% of their total boron after 128 days shaking. However, uptake of boron by white clover grown following application of the six borates in a glasshouse experiment lasting nine months was not related to their solubility in laboratory experiments. Providing that ores were finely ground (0.5–1 mm) and leaching was prevented, there were no significant differences in the availability of boron from any of the sources. Soil factors had a significant effect on uptake, particularly from the more soluble refined borates; a silty clay loam retained more boron than a sandy loam. Soil pH had less influence, plants grown on acid soils had higher concentrations of boron only early in the experiment. Top-dressing the borates increased uptake compared with incorporating them into the total weight of soil in the pot. Increasing particle size of the ores decreased the release of boron and made two of the ores less effective in comparison with the refined products. (McGrath and Ewens with R.P. White, Statistics and Dr V.M. Shorrocks, Borax Holdings Ltd)

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Nutrient reserves

Nutrient reserves in acid upland soils under forestry. Clear felling (CF), the conventional practice in which only the trunks of trees are removed, results in the return of most of the plant nutrients in the tree canopy to the soil. Newer techniques in which the whole tree is utilized (whole-tree harvesting, WTH) remove all of the nutrients. Jointly the Forestry Commission and the Institute of Terrestrial Ecology have compared these practices on a local ecosystem under Sitka spruce (*Picea sitchensis*) at Beddgelert Forest, North Wales, in an attempt to assess future productivity for forestry.

Our analyses of nutrient reserves in the stagnopodzol soil taken before and after harvest, show that the very acid (pH ~4) soils are poor in base saturation and in exchangeable and short-term reserves of K and other nutrients. Any nutrients returned especially under CF are poorly adsorbed and rapidly leached under the prevailing acid conditions, and exchangeable and short-term reserves of K in the soil would support only a few further cycles of forestry. However, other data suggest that under the acid conditions at Beddgelert, K-bearing minerals will weather quickly enough to supply the K requirements of conifers for tens of cycles or many hundreds of years. Other nutrients (Ca or P) are more likely to be limiting than K. (Goulding; Howe with Dr M. Hornung, Institute of Terrestrial Ecology, Merlewood and Mr P. Stevens, ITE, Bangor)

Soil structure, tillage and drainage

Shrinkage and soil structure. Shrinkage through drying is an important natural process contributing to the disintegration of large aggregates of clay soil into smaller ones in the field. The non-shrinking (predominately quartz) particles distort the shrinkage of the enveloping clay matrix, causing the latter to shrink anisotropically during the early stages of drying and possibly to crack eventually. The actual behaviour for a given clay mineral depends on the concentration and sizes of the non-shrinking particles.

To study this behaviour aggregates were made from kaolinite clay and glass beads (to simulate sand grains) and their cracking observed as they shrank under ambient laboratory drying. The aggregates did not crack if the beads were less than 1 mm diameter, but with larger beads the aggregates passed from a state where none cracked to one where all cracked as the proportion of the beads in the mixture increased. The proportion corresponding to the onset of cracking increased as the size of the beads decreased. With binary mixtures of 1 mm and larger beads the same trends occurred, but the onset of cracking tended to be inhibited by an increase in the proportion of 1 mm beads.

With more expansive clay minerals large differential shrinkage within the mass can set up additional strains which can also lead to cracking, even when no non-shrinking particles are present. The magnitude of the differential shrinkage depends on the drying rate. Further experiments, using bentonite, are in progress examining the interaction between rate of drying, particle size and particle concentration. The results provide a framework for further study on natural soils. (Towner; Dailey)

Simplified tillage and controlled traffic. The aim of this work is to reduce the cost of seedbed preparation. In conventional cultivation systems most of the soil surface carries wheel traffic during the growing of a crop and on many farms the main need for tillage is to remove the resulting compaction. Wheat and maize have been grown on compacted soil in laboratory experiments to distinguish the effects of mechanical impedance from those of poor aeration on root growth. With winter wheat, impedance and the restriction of oxygen to a flux less than 50 ng cm^{-2} min^{-1}, both slowed root elongation but the two did not interact. Maize roots suffered under both treatments which interacted positively. The relative importance

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of endogenous ethylene in controlling growth responses to poor aeration is being investigated for these two species. (Goss, Powell with W.C.T. Chamen, Institute of Engineering Research)

Cultivation and drainage. Many clay soils are only slowly permeable and require subsoil drains. The design of drainage schemes is based on experience with ploughed land, but ploughing such soils creates problems for seedbed preparation in autumn that cultivation, and the consequences for drainage design of adopting simplified tillage systems is not known. A field experiment, begun in 1978 at Brimstone (*Rothamsted Report for 1985*, 174 and *1986*, 159), compares yields of crops grown (a) with and without a mole and pipe drain system; (b) with conventional ploughing or direct-drilling. Each plot is separated from its neighbours to a depth of 1.1 m by polythene barriers and gravel-filled trenches containing a pipe drain. Surface water runoff and flow in the topsoil and through mole channels are measured together with the nitrate content.

Previous results have shown that, on average, drainage has increased yields of winter wheat by approximately 10%, with the benefits being slightly greater after direct-drilling than after ploughing. Significant interactions between drainage and cultivation have been found only with winter oats grown in 1983 and with oilseed rape in 1985. Winter oats, cv. Pennal, sown at 400 seeds m^{-2} in October 1986 followed winter wheat (*Rothamsted Report for 1986*, 159) and many wheat plants emerged with the oats, probably because the autumn was so dry. The number of volunteers was larger on the direct-drilled plots that on the ploughed. However, the larger population on the direct-drilled land did not result in a smaller yield of oats on microplots where volunteers were hand rogued after anthesis. Combine grain yields were significantly heavier on the direct- drilled, drained plots (6.70 t ha^{-1}) and on the ploughed undrained plots (6.60 t ha^{-1}) than on the direct-drilled undrained plots (6.24 t ha^{-1}) and the ploughed drained plots (6.02 t ha^{-1}). (Goss, Christian, Howse, Bacon with Mr G.L. Harris, Field Drainage Experimental Unit)

Soil mineralogy

Studies of iron oxide mineralogy by X-ray anomalous scattering difference methods. The inorganic fraction of a soil is almost invariably a multi-component mixture of minerals. Consequently it gives rise to a complex X-ray diffraction pattern containing many peaks, most of which are unresolved because of peak overlap. The X-ray anomalous scattering difference method developed recently allows the diffraction pattern from the iron oxide minerals (hematite, goethite etc) present in the soil to be separated from the pattern due to the matrix of other minerals, thus enabling identification and study of the iron oxides. The basis of the method is that the scattering of X-rays by an atom depends strongly on the wavelength for wavelengths close to an atomic absorption edge. Thus, for example, Fe atoms scatter X-rays of wavelength 1.937Å about 40% more strongly than those of wavelength 1.757Å. By collecting diffraction patterns at two or more wavelengths it is possible to obtain a difference pattern containing peaks only from those substances in which the selected atom makes a large contribution to the scattering. The method has now been applied for the first time to samples of soil clays, and difference patterns obtained for two iron-rich soils from Northamptonshire. This method has wide applicability in fields other than mineralogy, for example in studies of supported catalysts, and is a technique that seems certain to attract attention in the future. (Wood)

Randomly interstratified minerals. Work on the development of methods for the analysis of randomly interstratified clay minerals structures from X-ray powder profile refinement of their basal (oo1) reflections has now been completed. The basis of the technique is similar to that of Rietveld refinement, allowing least-squares estimation of the variable parameters

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in the model, but a more elaborate calculation of the diffraction pattern is used including explicitly the effects of disorder and small particle size. The method allows the determination of the spacing and relative amount of each interlayer type, together with other information such as atomic z-coordinates, site occupancies and the coherently-diffracting domain size. When applied to a hydrated Ca-montmorillonite and an interstratified illite-smectite soil clay the results were an improvement on those previously obtained from the same diffraction patterns by more conventional methods. This analysis has also shown the high degree of correlation between parameters such as the coherently diffracting domain size and the overall intensity of the pattern, suggesting that naive measurements of 'particle size' such as are often published are likely to be neither precise nor accurate unless great care is taken in the experimentation. Although designed primarily for use in clay mineralogy, the method may also have applications in studies of other disordered systems such as layered intercalation compounds and liquid crystals. (Wood)

The influence of diffractometer aberrations in X-ray Rietveld refinement. Rietveld refinement provides a method for determining crystal structures from powder diffraction patterns. Because it involves a point-to-point analysis of the diffraction pattern it is very sensitive to shifts in the positions of the Bragg reflections produced by diffractometer aberrations. The method, which is widely used, has therefore been much more successful with neutron powder diffraction data than with X-ray data because the aberrations in neutron diffractometers, which often have rather poor resolution, are relatively less important. It is essential that some account is taken of these systematic errors if the results obtained from Rietveld refinements are to be unbiased. Mark 3 of the Cambridge Crystallography Subroutine Library (CCSL) is currently under development, and we are writing improved Rietveld subroutines to incorporate these effects. The new program should produce a considerable improvement in the accuracy of crystal structures determined from powder data. (Wood with Dr W.I.F. David, SERC Rutherford Appleton Laboratory)

Studies of synthetic and soil-occurring aluminium goethites. It has been suggested that the degree to which Al ions substitute for Fe ions in the crystal structures of iron oxides such as goethite (α-FeOOH) and hematite (α-Fe_2O_3) may be a valuable indicator of pedogenic and other weathering environments. However, because these oxides occur in soils as components in a mixture of minerals, simple chemical analysis cannot be used to find their composition. X-ray diffraction is probably the technique most suitable but it is usually applied very crudely: for example, the Al content of goethite is often inferred from the Bragg angle of a single reflection. It seems likely that the use of differential X-ray diffraction combined with profile refinement, techniques developed recently at Rothamsted, will provide a much better analysis. These methods are now being tested in a study of synthetic aluminous goethites of known chemical composition. Essentially, a model of the goethite diffraction pattern is constructed with the Al content as one of the adjustable parameters and incorporated into a least-squares profile refinement program developed for the analysis of differential diffraction patterns. The crystal structures of these goethites are also being refined using the Rietveld method. (Wood)

Angle-dispersive X-ray powder diffraction at tuneable wavelengths using a laboratory Bremsstrahlung source and a position-sensitive detector. Some modern X-ray powder diffractometers are constructed using high-resolution focussing optics to define the incident beam and a position-sensitive detector to measure the diffracted X-rays. These instruments cover an angular range of 60° or more simultaneously and are therefore about 100 times faster in operation than conventional diffractometers. Ideally experiments such as X-ray anomalous scattering difference studies require an X-ray source of tuneable wavelength, and

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it now seems likely that this can be achieved in the laboratory by combining a high power X-ray generator with a diffractometer of the type described above. A pilot experiment to test this system has been made in which diffraction patterns were compared using as the X-ray sources (a) the Kα spectral line from a cobalt-anode X-ray tube and (b) the Bremsstrahlung ('white') radiation from a 2kW tungsten-anode X-ray tube. The patterns using the Bremsstrahlung source were about 400 times weaker but had apparently identical resolution, since this is defined almost wholly by the diffractometer's optics. The success of this pilot study indicates that by utilizing a 15kW rotating-anode X-ray generator and a modified diffraction geometry it will be possible to construct an instrument, operating in the laboratory at tuneable wave-length, capable of measuring a powder diffraction pattern in a few hours. (Wood, with Dr D. Puxley, British Gas and Dr C. Baxter, Rolls Royce Ltd)

Pedological studies

Coversands in Lincolnshire. The blanket of coversands between the Trent Valley and Lincolnshire Wolds is being studied to clarify their age, mode of deposition and variability. Some of the sands, deposited by the wind in cold arid conditions about 10 000 – 11 000 years ago, can be distinguished from older glacial sands by detailed particle size analyses. The results also show that the modal grain size of the windblown sands decreases regularly eastwards, indicating that they were derived from the west. (Catt and George, NERC/CASE student)

Glacial sequence in North Humberside. Information relating to older parts of the Quaternary succession in North Humberside was obtained from boreholes drilled at Easington by Soil Mechanics Ltd under contract to BP Petroleum Development Ltd. These were drilled almost completely in till and reached to depths (−25 to −27 metres OD) close to the bedrock (Chalk) surface. Particle size and mineralogical analyses of samples taken from various depths between −6 and −27 m OD allowed comparisons to be made with the standard sequence of tills in eastern England. Principal coordinate and canonical variate analyses of sand mineral suites from the samples showed that the till penetrated by the boreholes corresponded with the Wolstonian Basement Till, which is therefore the oldest glacial deposit preserved in North Humberside. (Catt with Digby, Statistics)

Man-made urban soils. The uniform black deposit (dark earth) occurring on many Roman urban sites in Europe was analysed mineralogically to help clarify its origin. At many sites an iron-rich olivine (fayalite) was found in abundance in the dark earth but not in associated deposits. Its identification was confirmed by electron probe in the Geology Department, Imperial College, London. This mineral occurs naturally in some volcanic rocks, but it is rare in soils and sediments because it is easily weathered. It also occurs in some furnace slags, which suggests that dark earth originated partly as a waste product of small-scale urban metal production. Microscopic fragments of lead glass were also found in many samples, and this may represent another aspect of the urban industry at the time dark earth was formed. (Catt and Farrington)

Spatial variation

Soil properties are distributed over the land surface in ways that are both random and spatially dependent: technically they are *regionalized variables*. We have adapted the theory, developed largely by and for mining engineers for analysing such distributions and predicting their values, to the agricultural context. We can now estimate the concentrations of soil constituents, crop yields and other features of agricultural importance without bias, efficiently and with known error from sample data, taking account of the spatial dependence and sampling configuration.

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Geostatistically constrained classification. The technique represents a substantial break with the traditional approach to spatial prediction of soil properties based on classification. Indeed it does not recognize different classes of soil. Nevertheless there are many situations for which farmers need classifications of soil. We have therefore devised new methods that combine both multivariate and spatial information in data to classify the soil and locate soil boundaries. One method, split neighbourhood kriging, places boundaries optimally between segments on sampled transects. (Wackernagel, Webster & Oliver (1988) In: *Classification and related methods of data analysis*. Ed. H.H. Bock, Amsterdam: North- Holland). The other operates in two dimensions, and creates distinct parcels of land by considering both the similarity between sampled sites and their spatial dependence. The results are locally optimal. (Oliver & Webster *Mathematical Geology* (1988) **20**, in press). Both techniques have uch potential for classifying land and its cover using remote sensing. (R. Webster; Munden with Dr M.A. Oliver, Birmingham University and Dr H. Wackernagel, Ecole des Mines de Paris)

Variation caused by irrigation. Irrigation with unsuitable water or inadequate drainage in dry regions can make soil more alkaline and salty, exacerbating any natural variation in the soil in these respects. It is little consolation to the farmer to know that his soil is affected only in patches, because a substantial problem has still to be avoided or overcome.

For more than 50 years a plot of land on dark cracking clay on the Experimental Station at Wad Medani in the Gezira of Sudan has been irrigated by flooding and cropped intensively while an adjacent plot has been maintained in its natural state. By spatially analysing data from a recent detailed survey we showed that there has been no increase in the *average* pH, electrical conductivity or sodium content of the soil. There has, however, been a substantial increase in the *variation*. The natural pattern of variation that extends linearly parallel to the river has been magnified, though not to the extent that critical values have been exceeded. Also, a wholly new linear pattern on a finer scale and approximately perpendicular to the original one has been created. We attribute the second to the positions of temporary wetting fronts during irrigation. (R. Webster; Munden with Mr I.M. Buraymah, Soil Survey Administration, Sudan)

Remote sensing

Short-range variation of soil and winter wheat yields at Brooms Barn. Variations in depth and texture of soils within a field often result in differences of crop growth and yield, especially in dry summers when some soils are more drought-prone than others. In 1987 we tried to use these crop differences on Marl Pit field at Broom's Barn to evaluate multi-spectral reflectance measurements as a means of predicting yields. The yields from four of the five soil series identified on this field were not significantly different, probably because soil moisture deficits remained small throughout the growing season; as a result no reflectance factors could be used to predict yield. The yield from Weasenham series (typical argillic brown earth) was 3% less than the mean yield, and although plots on this soil gave a similar number of grains per unit area to plots on the other soils, the mean grain mass was 3% smaller. A clay-enriched argillic horizon, which occurs only in the Weasenham series in this field, may have restricted root growth, which possibly inhibited nutrient supply for grain-filling in later growth stages. (Catt and R. Webster; Ashcroft and Munden)

Prediction of Broadbalk yields. Previously (*Rothamsted Report for 1986*, 164) we have noted that the ratio of red to near infrared reflectance of cereal crops approximately one month before harvest is correlated with final grain yield. On five occasions during 1987 a radio-meter held 2 m above winter wheat grown on 13 Broadbalk plots was used to measure the

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spectral reflectance. Final grain yields were strongly correlated with ratios of red to both near and middle infrared reflectance between 13th May and 13th July (r = 0.88 to 0.95) but less so (r = 0.75 and 0.72 respectively) on 27th July, approximately one month before harvest. Infrared reflectance increases with increasing amounts of green tissue, especially spongy mesophyll, and red light is absorbed during photo-synthesis, so the weakening of the correlation towards harvest probably resulted from a decrease in photosynthetic rate. The strong correlations earlier in the season mainly reflected N manuring, and suggest that spectral reflectance measurements have potential for early prediction of cereal yields and correction of N deficiency.

Flights over Broadbalk at a height of 600 m with a multispectral scanner were also made on 2nd May and 25th July, and the reflectance of 97 of the plots was measured. The accuracy of measurements from the air is less than those at ground level because of atmospheric interference, such as absorption of infrared reflectance by atmospheric water vapour; nevertheless, on 2nd May the correlation between red to near infrared ratio and final yield was 0.77. Like the ground level measurements it was weaker (0.48) in late July. These results suggest that multispectral measurements from an aircraft can be used to predict yields early in the season, though not as precisely as ground level measurements. Future research should concentrate on the interpretation of ground-based radiometry. (Catt and R. Webster; Munden and Ashcroft, with Dr P.J. Curran, Sheffield University)

Analytical and techniques

Analyses. 247,000 digestions and analyses were done this year; 38.5% more than last year. These analyses derived from 20 000 samples of which 6.8% was done for other departments. (Cosimini, Fearnhead, Gregory, Skilton, Snellgrove and Williams)

Crop samples handled in the Fertilizer Building in 1987. About 10 500 samples were processed in 1987, some 2000 more than in the previous year; the increase was from extra grass and grain samples. After processing, many of the samples were ground and sent for analysis in the Analytical Section. The weight of 1000 grains was determined on many of the grain samples. (Cundill)

Automatic data recording. The data recording system previously described has been further developed by the acquisition of blank perforated labels of a tough waterproof material (*Rothamsted Report for 1986*, 165). A new computer program has been written to print sample labels whose barcoded information can be read by the logging computer. (Darby)

Staff and visitors

A.E. Johnston was appointed Head of the Soils and Crop Production Division and also Head of the Soils Department on 17th August 1987.

The Department was saddened to hear of the death in June of J.H. Rayner who had retired only in January.

Mary Fearn and V.C. Woolnough both retired having completed 15 years and 22 years respectively. Jennifer H. Large transferred to Insecticides. Margaret Wootton, D.S. Hayman, P.F. North and E.G. Youngs all left in March. P.M. Williams transferred to the Agricultural Genetics Company (AGC) in July to work on microbial inoculants. Margot H. Ewens completed the work funded by Borax and left in June and Kate G. Copestake left in July having completed her three-year contract funded by Norsk Hydro Fertilizers Ltd. Ingrid Arias, J.C. Dodd and Irene Koomen completed their European Economic Community (EEC) contract and Ingrid Arias transferred to an AGC-funded project. Jane C. McLeod, funded by British

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Technology Group (BTG) for one year, left in July and Marie Rogers in March and Lisa Warburton in May.

Margaret J. Glendining arrived in August to model the supply of nitrogen from soil and N.L. Carreck came in November to work on the effect of husbandry practices on the malting quality of barley, both posts being funded by the Home-Grown Cereals Authority (HGCA). P.G.C. Ellis, an AGC employee, arrived in August to work on *Rhizobium* inoculum production.

A.E. Johnston was invited to the 2nd Cary Conference on Long-Term Studies in Ecology at Mill Brook, New York; together with K.W.T. Goulding and Dr K.C. Jones (Lancaster University) he also presented posters at an EEC symposium 'Effects of air pollution on terrestrial and aquatic ecosystems', Grenoble, France. A.E. Johnston and S.H.T. Harper both presented papers at another EEC meeting entitled (Energy saving by reduced soil tillage' at Göttingen, West Germany in June. R. Webster spent five weeks as a guest of the South African Forestry Research Institute at its Saasveld Research Centre in Cape Province, South Africa, applying geostatistics to pre-investment soil surveys and site monitoring. He also lectured on geostatistics at Michigan State University, East Lansing, U.S.A. D.S. Jenkinson presented papers with D.S. Powlson, who also chaired a session, at the International Symposium on 'Advances in nitrogen cycling systems in agricultural ecosystems' at the University of Queensland and they also attended an EEC meeting on nitrogen transformations in soil and their manipulation in arable agriculture at Leuven, Belgium in January. In May D.S. Jenkinson visited research centres in New Zealand, including Lincoln College, Canterbury; Department of Scientific and Industrial Research (DSIR) Soil Bureau Lower Hutt; Massey University, Palmerston North and Ruakura Soils and Plant Research Station, Hamilton and in June two weeks was spent at the Waite Agricultural Research Institute in Adelaide and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Dryland Crops and Soil Research Unit in Perth, Australia. D.S. Powlson, at the invitation of the Wheat Research Council of Australia, gave lectures in the Department of Australian Environmental Studies at Griffith University, Brisbane and visited (CSIRO) Soils Division and the Waite Agricultural Research Institute, Adelaide. He also visited Malaysia to discuss current research on acid sulphate soils and on methods of increasing the organic matter content of wastes from open-cast tin mining. J.A. Catt attended the XIIth Congress of the International Union for Quaternary Research (INQUA) in Ottawa, Canada when he was elected President of the Palaeopedology Commission (VI) of INQUA. M.J. Goss, financed by the Treaty of Windsor Programme, visited Portugal in April and October to work on factors affecting the growth of winter wheat; he also lectured on soil management at the International Maize Improvement Centre at the Maize Research Institute, Belgrade, Yugoslavia in September. J.M. Day visited the Bangladesh Agricultural Research Institute, Dacca, in March, in connection with inoculum production, for the Food and Agricultural Organisation (FAO) and in July he visited Tunisia for the AGC and the FAO to assess the value of pasture legumes in rotation with cereals. Christine M. Hepper gave two invited papers at the 7th American Conference on Mycorrhiza in Florida and two more at a meeting on ecto- and endomycorrhizas in Helsinki. In February Penny R. Hirsch visited Brussels and in March the National Institutes of Health, Bethesda, U.S.A. to discuss setting up a joint USA/EEC database for risk assessment when releasing genetically manipulated microorganisms. With R.C. Snellgrove she presented a poster at the EEC Biotechnology Action Programme (BAP) Contractors' Meeting in Louvain, Belgium and in August helped prepare, in Brussels, a reply to the European Parliament on risk assessment experiments. In September and October she visited Huazhong Agricultural University, Wuhan, People's Republic of China to carry out joint research in the new Biotechnology Centre and also gave lectures in Huazhong and Nanjing Agricultural University, a visit closely followed by attendance at another EEC/BAP project meeting at the University

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of Bayreuth, West Germany, to discuss the research project with collaborators and together with John Spokes presented a paper at an EEC Conference on 'Risk assessment for the release of genetically manipulated microorganisms'. S.P. McGrath presented a keynote paper at the 6th International Conference on Heavy Metals in the Environment in New Orleans in September. K.W.T. Goulding and I.G. Wood attended the 20th Colloquium of the International Potash Institute (IPI) on 'Methodology in soil K research', Vienna, Austria, in June and presented invited papers. I.G. Wood also presented a paper at the International Union of Crystallography XIVth Congress and General Assembly, Perth, Australia and attended the International symposium on X-ray Power Diffractometry at Fremantle, Australia he also lectured in the Soil Science Department, University of Western Australia and at the CSIRO Division of Soils, Adelaide. G.W. Cooke visited Madrid to give a series of six lectures in the Curso Internacional Fertilidad de Suelos y Nutricion Vegetal in June and N.W. Pirie attended a Pugwash meeting at Gmunden, Austria.

The Division was pleased to note the election of R. Webster as a Fellow of the Royal Society of Arts and the award to R.C. Snellgrove of a Ph.D. by the Council for National Academic Awards (CNAA).

Dr R.G. Jörgensen, a postdoctoral Fellow, from the German Research Foundation (DFG) arrived in September for one year to work on microbial survival mechanisms in soil. Dr Marta Rolfo from Uruguay and Mr G. Verley from Belgium both arrived in July to work on mycorrhizas, Dr Rolfo left in December. Dr M. Saito arrived from Japan in November to work on localized phosphate uptake by mycorrhizal plants. J. Ocio, a postgraduate student from Spain, is spending ten months with us measuring changes in soil microbial biomass following straw incorporation, and P. Widmer, postgraduate student from Germany will be here for four months measuring the turnover of soil microbial biomass nitrogen.

Others who completed their studies were Dr D.R. Vencatasamy, on the effect of mycorrhizas on manganese uptake, who returned to Mauritius in September; Dr K. Inubushi, on the effects of waterlogging on soil microbial biomass, who returned to Japan in July; Dr Helen Setatou, on the use of ^{15}N to determine the efficiency of use of N fertilizers, who returned to Greece in August and Mr N.E. Møller on foliar application of ^{15}N-labelled urea to wheat, who returned to Denmark in February.

We welcomed for three years J. Wu from China who registered for a Ph.D. at Reading and is modelling the turnover of organic carbon in agricultural soils. Rosenani Abu Baker, Orpah Farrington, B.A. Powell, R. Leitch, R.J. Milling and L.J. Clark all continued their studies and B.M. Smallfield completed his studies and returned to New Zealand.

The following NERC/CASE students arrived, P.M. Atkinson, from Sheffield University, to study radiometric sensing of soil and crops and design efficient sampling schemes for it, Lesley C. George, from Nottingham University to study 'Coversands' of Trent Valley and M.D.A. Rounsevell, from University of Newcastle to study interparticle bonding.

CROP PRODUCTION DEPARTMENT

Much of the Physiology and Environmental Physics Department programme, which seeks to identify the key physiological attributes that contribute to both yield and quality of arable crops, has been subsumed into this new department. Field studies are made on crops grown both in the multidisciplinary experiments (see p. 17) and in others which are supported by appropriate laboratory based experiments. Much of the work is reported on a crop by crop basis. The way in which the data is being used in crop modelling is also described. Some of the agronomic work undertaken by members of the Department is featured in the Multidisciplinary Section of this Report.

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Winter wheat

Among various topics currently being studied are the agronomic and physiological factors that influence protein yields in grain and the predictability of yields. Crop modelling is providing the quantitative framework for these studies, and is also the basis of a practical scheme for predicting development of winter wheat.

Prediction of yield. Since 1982, estimates have been made of the radiation intercepted by winter wheat after anthesis under the best treatment combinations in the multidisciplinary experiments. Such calculations clearly indicated that 1984, the year with the largest yield, was exceptional. Although numbers of grains per unit ground area were less than average (19 200 cf. 20 000 m^{-2}), the cool weather prolonged the grain-filling period and high daily mean radiation resulted in total radiation interception of 650 MJ m^{-2} compared with a six-year mean of about 570 MJ m^{-2}. The relationship between yield and radiation intercepted was weaker for the other years. Low yields (8.5 t ha^{-1}) in 1987 compared with the six year mean, were associated with cool, dull weather (daily average temperature 15.1 cf. 15.9°C and radiation 15.1 cf. 17.3 MJ m^{-2}) so that the radiation intercepted during the period of grain filling was near the average for the last six years. Grain numbers in 1987 (best treatment 18 000 grains m^{-2}) were particularly low. In this series of experiments at Rothamsted, grain numbers have been remarkably consistent, rarely exceeding about 20 000 m^{-2}. With this limitation on the number of sinks (grains), it is not surprising that the potential for post-anthesis growth can be a major determinant of yield (as in 1984). When grain numbers are particularly low, as in 1987, the potential for assimilation after anthesis is less relevant. Further elucidation of these issues will be important when interpreting the variability of grain protein. (Day; Scott)

Responses to foliar urea. Foliar application of fertilizer N solutions late in the growing season may be useful for several reasons. First, to supplement earlier applications, especially if these were subject to loss. Second, as part of a strategy for minimizing loss by supplying the total N requirement of a crop in several separate portions. Third, to target fertilizer N to specific parts of a crop; an example of this is to increase the protein content of wheat grain.

Agronomic effects. In 1986 recoveries of foliar-applied N were measured using ^{15}N-labelled urea solutions sprayed onto wheat (cv. Avalon) at weekly intervals from three weeks before anthesis to two weeks after. Each application of 40 kg N ha^{-1} was divided into two 20 kg ha^{-1} portions, separated by 1–2 days, to minimize the risk of leaf scorch. The spring top-dressing, applied to the soil in the normal way, was 210 kg N ha^{-1}, more than sufficient to achieve maximum grain yield.

At harvest, 70% of the foliar-applied N given at anthesis, Zadoks growth stage (GS) 65 was recovered in the above-ground crop. Recovery was less for the earliest and latest times of application; 64% for that given at GS 39 and 58% for that given at GS 73. These recoveries are similar to those measured previously for ^{15}N-labelled fertilizers applied to the soil in spring. Of the foliar N applied at anthesis (GS 65) 64% was recovered in grain, representing 92% of the labelled N in the crop, a slightly larger proportion than with soil-applied N given earlier. Each of the foliar applications (40 kg N ha^{-1}) increased %N in grain to the same extent as an additional 40 kg N ha^{-1} applied to soil in spring. (Powlson, Poulton, Penny, Jenkinson and Hewitt with N.E. Möller, visiting student)

Physiological responses. The dynamics of N uptake, incorporation into leaf proteins, translocation to grain, and the consequences for the photosynthetic function of the flag leaf during senescence were examined in 1987, in an extension of the multifactorial winter wheat experiment (p. 24). Plots of September-sown wheat, grown after oats and without winter

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N, were given a total of either 0, 80 or 200 kg N ha^{-1} as four dressings to the soil between February and May, and either 0 or 40 kg N ha^{-1} as urea applied to the foliage at the end of May, when the flag leaves had fully emerged.

Growth and N uptake. Crops that received either 0, 80 or 200 kg ha^{-1} of spring N, gave yields without foliar N of 3.6, 6.2 and 8.0 t ha^{-1} respectively. Foliar urea increased yields by 0.5 t ha^{-1}, irrespective of the amount of spring fertilizer. This unusual increase in yield from late foliar N was associated with both more and heavier grains.

At anthesis, three weeks after urea application, treated crops contained 17 kg N ha^{-1} more than untreated, an amount very similar to the additional uptake by a crop grown in 1986 given 60 kg N ha^{-1} to the soil at the same stage of growth. In 1986 the late N gave an increase in grain %N of 0.12. Equivalent data for the 1987 crop are not yet available, but the benefit this year will probably be much less, because yield was increased by 5% whilst N uptake at anthesis was only increased by 9%.

The response of yield to foliar N, and particularly the effect on numbers of grains, suggest that the crop was short of N close to anthesis. Canopy cover for the crop that had received 200 kg N ha^{-1} in the spring was nearly complete, and the benefit for leaf area was not apparent until canopy senescence began some time after anthesis. (Milford and Powlson; Mullen and Stevenson)

Urea uptake by the flag leaves. Three hours after the application of the urea spray, the surface deposit of urea contained 1.5 mg urea g^{-1} fresh leaf mass. One day later (and after 2.7 mm of rain) the amount of urea had decreased by 65% and after four days was barely detectable. Urea content within the leaf tissue was 0.2 mg g^{-1} fresh mass three hours after the spraying, but after one day had decreased by 75% and was minimal after four days. Urease activity was similar in all treatments when the tissues were sprayed and increased with leaf age, irrespective of spring N or urea treatment. Nitrate reductase activity increased with increasing spring N dressings, but was not affected by urea application. This suggests that urea uptake and metabolism occurred rapidly without induction of urea-metabolizing enzymes, and would not affect the capacity of leaves to use nitrate subsequently. (Lawlor; Mitchell, Driscoll and Ruffle)

Nitrogen supply and photosynthesis. Photosynthetic responses to light and CO_2 were measured on leaves attached to plants in the field, and also on detached leaves brought into the laboratory, to define the potential photosynthetic capacity of the leaves.

The field measurements showed little increase in the quantum yield of photosynthesis (measured at low irradiance) with additional spring nitrogen or foliar urea. The maximum rate of photosynthesis at high irradiance and ambient CO_2 concentration increased substantially with increasing spring N dressing, and foliar urea increased the rate most for the crop given no spring N. The carboxylation efficiency at saturating light, averaged over the life of the flag leaf, increased greatly with additional nitrogen but the maximum rate at high CO_2 concentration did not. Urea increased the efficiency substantially when applied to a crop given no spring N but had little effect on the other treatments. Urea slightly increased the maximum rate of assimilation in saturating light and CO_2, averaged over the season, for the crop given no spring N but for the other treatments it caused a small decrease.

Laboratory measurements of photosynthesis (at 20°C) confirmed the field observations, but suggested somewhat greater photosynthesis at high light and ambient CO_2 for crops receiving spring N; the difference between laboratory and field may result from the cooler temperatures during measurements in the field this year. (Lawlor, Chalabi, Day and Young; Harrison, Driscoll and Scott)

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Composition of flag leaves. Flag leaves in crops given 80 or 200 kg N ha^{-1} in spring contained some 40% and 70% more chlorophyll per unit leaf area when fully expanded than those grown without spring N. After full emergence, chlorophyll content decreased only slightly until the end of June, but substantially after that in all treatments. Urea applications prevented the early decline in chlorophyll and delayed the late decrease. The ratio of chlorophyll *a* to *b*, which indicates the composition of the light harvesting apparatus, was similar in all N treatments, and decreased as leaves aged. Soluble protein contents of young flag leaves were 1.5 and 1.8 times greater with 80 and 200 kg ha^{-1} of spring N compared to none; the content decreased with leaf age. Urea application maintained a larger soluble protein content for most of the period in each treatment; as in 1986, about 60% of the soluble protein was ribulose bisphosphate carboxylase-oxygenase (Rubisco).

Thus applications of N fertilizer during growth of the flag leaf increased the amounts of the pigments and proteins and increased the longevity of leaves. Application of urea to mature leaves slowed the decrease in their protein and pigment content and therefore maintained higher potential rates of photosynthesis for longer. (Lawlor; Mitchell, Driscoll and Ruffle)

Modelling the response of canopy photosynthesis to changes in leaf photosynthetic parameters. A simulation model has been developed to estimate canopy photosynthesis on the basis of observations of leaf photosynthesis. It has been used to estimate the magnitude of the changes in canopy photosynthesis that may be expected if leaf photosynthetic characteristics can be improved.

The model is based on a method, developed by Spitters *et al* (*Agriculture and Forest Meteorology* (1986) **38**, 217-242), in which the radiation incident on the crop is divided between direct and diffuse beam so that photosynthesis of directly and diffusely illuminated leaves can be calculated separately. An asymptotic exponential equation, parameterized by the maximum photosynthetic rate (plus dark respiration) at high light (A_m) and the quantum efficiency (ϵ) describes the leaf photosynthetic response to light.

In the UK climate, where the mean daily shortwave radiation in June is only about 18 MJ m^{-2}, the likely benefit from increasing the maximum leaf photosynthetic rate by 10% would only be a 2.5% increase in canopy photosynthesis. If increases in maximum photosynthetic rate were accompanied by a decreased leaf area index, even this small benefit could disappear. A direct corollary is that improvements in quantum efficiency could give a much larger benefit. (Chalabi and Day)

Prediction of apical development of winter wheat. A computer-based scheme for predicting early development of winter wheat has been developed. The scheme, which uses an improved version of the AFRC development model, can be run each week during late winter and spring, using long-term average temperatures updated with daily mean temperatures recorded at meteoro- logical sites as they become available. Extra information about development in the current year is obtained by monitoring a few crops; each week this information is incorporated into the prediction scheme to improve the accuracy of the model. Not only are the apical development stages of double-ridges and terminal spikelet predicted but also the growth stages ear at 1 cm, and 1st, 2nd and 3rd node detectable (GS30−33), corresponding to early stem extension. Though the intervals between these growth stages are consistent and predictable, the timing of stem extension varies relative to apical development so that, at terminal spikelet, more stem extension has taken place for early-sown than for late-sown crops.

There is no clear evidence of differences between cultivars in responsiveness to temperature or photoperiod, other than the difference between winter-type cultivars, which have a vernalization response, and spring-type cultivars, which do not. The wheat cultivars currently being grown are allocated to one of seven distinct classes based on duration of development

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intervals. The scheme is now being implemented by ADAS Eastern and Northern Regions and predictions in the 1987/88 growing season will be supplied to those subscribing to the ADAS Service. (Travis, Day and Chalabi)

The nitrogen requirement of wheat after various crops. A series of annual experiments, started in 1985, have compared yields of a number of combinable break crops and their effect on following winter wheat. The crops were: winter (w.) beans, w. oats, w. rape, w. peas, w. wheat, spring (s.) beans, s. lupins, s. peas, sunflowers and no crop (fallow). The succeeding wheat, cv. Avalon, tested none and a spring application of N fertilizer, the amount of which was calculated using a nitrogen balance technique to achieve equal yields after all preceding crops.

Mineral N in the soil (0–90 cm) was measured soon after the wheat emerged, it ranged from 13 kg NO_3-N ha^{-1} following w. oats, to 95 after fallow. In the spring, amounts ranged from 16 after w. oats, to 55 kg NO_3-N ha^{-1} where the wheat had failed following lupins. The latter plots were resown with spring wheat, yields are not given here. The calculated fertilizer N requirement ranged from 190 to 240 kg N ha^{-1}.

Yield without spring N ranged from 2.18 after oats, to 5.28 t ha^{-1} after fallow. Where spring N was applied, yields following seven of the nine preceding treatments were not significantly different averaging 7.93 t ha^{-1}with a range of only 0.35 t ha^{-1}. Yields outside this range were those of the second wheat crop (6.73 t ha^{-1}), and after w. rape, (8.63 t ha^{-1}, the largest yield). (Darby, McEwen, Hewitt and Yeoman)

Application of a nitrification inhibitor with liquid fertilizer for winter wheat. In 1985 liquid urea-ammonium nitrate (UAN), without or with the nitrification inhibitor dicyandiamide (DCD), was sprayed on to Avalon winter wheat to supply either 160 or 240 kg N ha^{-1} in two equal applications in February and March, or March and April, or February and April or in four equal applications in February, March, April and May. The experiment was repeated with the addition of a single application in either March or April in 1986 and in either February or April in 1987. In 1987, also, UAN was compared with 'Nitro-Chalk' when each was applied in two equal applications in March and April or as a single application in April.

In 1985 DCD increased grain yield in all comparisons except one and, on average, from 8.58 to 8.93 t ha^{-1}. Percentage of N in the grain was always larger with than without DCD (mean 2.00 vs. 1.89) as was uptake of N (mean 152 vs. 139 kg ha^{-1}). In 1986 DCD had no significant effect on either yield or percentage of N or uptake of N. In 1987 yields were small because of take-all. DCD increased yield when the single application of UAN was applied in February, from 5.75 to 6.11 t ha^{-1}, but otherwise had little effect. Yields from the single application with DCD in February and from the single application without DCD in April were identical. Mean yields with 'Nitro-Chalk' and UAN without DCD were 5.88 and 6.02 t ha^{-1} respectively. (Penny, Darby and Hewitt)

Grain quality. Work on the quality of winter wheat grain (*Rothamsted Report for 1985*, 170 and *for 1986*, 153), was continued. 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 (cv. Avalon) from a multifactor experiment (see p. 24) and from Broadbalk. On Broadbalk cvs. Brimstone and Squarehead's Master were compared (see p. 127). Specific weights only were determined on cv. Mercia which was grown with a range of N rates after grass-clover leys ranging from one to six years' duration at Woburn. Specific weights were always determined on the 1.0–3.5 mm size at 85–86% dry matter.

In the multifactorial experiment the treatments (previous crop rape or oats, September or October sowing, division and timing of N) had little effect on grain size or specific weight. About 97% of the yield was in the 2.0–3.5 mm fraction. Specific weight was a little larger

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with October than with September sowing and with divided than with single N application in spring; the mean value was 70.4 kg hl^{-1}.

On Broadbalk (cv. Brimstone) the mean percentage of grain in the 2.0–3.5 mm fraction in the first wheat after a two-year break was the same as in the multifactor experiment (97%) and was only slightly less in the tenth or twenty-first wheat after fallow (96%); it was little affected by rate of N, and, unlike 1985, by not giving K since 1843. Mean specific weight of the first wheat (69.9 kg hl^{-1}) was larger than that of either the tenth (66.4) or the twenty-first (67.9). Unlike 1985, applying N decreased specific weight (on average from 69.4 kg hl^{-1} without N to 66.3 with 240 kg N ha^{-1}). Where K had not been applied since 1843 specific weight of the first wheat was decreased by only 1 kg hl^{-1} but of continuous wheat by 3 kg hl^{-1}. When both cultivars were grown as the tenth wheat after fallow 94% of the yield of Squarehead's Master and 96% of Brimstone was in the 2.0–3.5 mm fraction. The mean specific weight of Squarehead's Master was smaller than that of Brimstone (64.9 vs. 66.4). Like Brimstone, specific weight of Squarehead's Master was decreased by applying N, but, unlike Brimstone, not by withholding K.

In the experiment on the sandy soil at Woburn specific weight increased with each 50 kg increment of N up to 200 kg N ha^{-1} after the one-year ley (72.0 to 75.2 kg hl^{-1}) and the two-year (73.0 to 75.1), but only up to 100 kg N ha^{-1} after the three-year ley (73.5 to 74.5) and the four-year (74.2 to 74.8). N had no effect after the five- and six-year leys.

The effects of N rates were again inconsistent in 1987, decreasing specific weights on Broadbalk but increasing them in the experiment at Woburn. Specific weights in 1987 were smaller than in 1985 and much smaller than in 1986. For example, in the multifactorial experiments Avalon had a mean specific weight of 70.4 in 1987 but 77.1 in 1985 and 80.1 in 1986; grown in the continuous wheat sequences on Broadbalk, Brimstone had a specific weight of 67.2 in 1987 but 70.9 in 1985 and 75.2 in 1986. Seasonal effects therefore were just as large as treatment effects. (Penny and Hewitt)

Winter barley

Factors limiting yield and quality. Winter barley varieties can often be manipulated with the intention of producing either malting or feed quality grain by agronomic practice. The importance of various factors have been assessed on one such cultivar–Magie. In addition the effect on crop structure, of the nitrogen supply in the autumn and winter, and the effects of take-all have also been investigated.

Where barley followed oats or barley, yields were 6.70 and 5.23 t ha^{-1} respectively, not as large as previously. Delaying the application of spring N from March to April reduced yield by 0.85 t ha^{-1} whilst the control of leaf diseases by fungicides increased yield by 0.83 t ha^{-1}. Increasing the nitrogen supply to the crop in the autumn from 49 to 75 kg N ha^{-1} increased maximum tiller numbers by approximately 200 stems m^{-2} and with an additional 25 kg N ha^{-1} in February, yield by 0.77 t ha^{-1}. (Darby)

Oilseed rape

Studies of oilseed rape provide information on factors affecting yield, the radiation conversion efficiency of the crop and on seed shedding, while extensive crop sampling this year has provided material for analysis of glucosinolate content and distribution. This will help establish how best to achieve low glucosinolate concentrations in the harvested seed in order to meet EEC quality requirements.

Factors affecting yield. Following the decision by the EEC to remove the crushing subsidy from low erucic acid rapeseed after 1991, the multifactorial experiment at Rothamsted was

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changed to compare Bienvenu (low erucic acid), with Ariana (low erucic and low glucosinolate).

Establishment and weed control in 1986 were good. Bienvenu flowered before Ariana and the prolonged flowering period caused by differing sowing dates and cultivars resulted in large numbers of pollen beetles which adversely affected the pod set of Ariana. Wet weather prevented the planned earlier harvest of Bienvenu so both cultivars were harvested at the same time. Even though some seed of Bienvenu was shed it yielded significantly more than Ariana, 4.00 vs. 3.72 t ha^{-1}. The application of fungicides, and a stem-shortening growth regulator increased yield from 3.68 to 4.04, and 3.55 to 4.17 t ha^{-1} respectively.

Bienvenu contained significantly more oil than Ariana, 49.5 vs. 46.4% oil in dry matter. Increasing the amount of N fertilizer from 150 to 250 kg N ha^{-1} depressed oil content from 48.7 to 47.2%, and the application of fungicides and growth regulator resulted in small improvements in oil content. Yield of oil was larger from Bienvenu than Ariana, 1786 vs. 1552 kg ha^{-1}, and was significantly improved by the application of fungicides and the growth regulator. (Darby)

Forms and timing of spring N. The experiment described last year (*Rothamsted Report for 1986*, 148) was repeated, comparing Mikado with Ariana. The rape was sown at 8 kg ha^{-1} without seedbed N on 3 September. In spring none or 200 kg N ha^{-1} was applied as urea or calcium ammonium nitrate (CAN) either as a single dressing, or divided in six ways spanning four occasions, 23 February, 16 March, 9 and 27 April.

Yield was much smaller than in 1986 probably because wet weather delayed harvest. Without N both Ariana and Mikado yielded 1.13 t ha^{-1} (90% DM). There was no significant difference in yield from applying 200 kg N ha^{-1} either as CAN or urea; and, averaged over these two forms of N, timing of the spring application did not significantly effect yield either. However, the largest yield of Ariana from urea (2.78 t ha^{-1}) was achieved when all the N was applied on 23 February, and from CAN (2.84 t ha^{-1}) when 150 kg was applied on 23 February and 50 kg on 16 March. By contrast the largest yield of Mikado from urea (2.97 t ha^{-1}) was achieved when the N was applied over a longer period, 100 kg on 23 February and 50 kg on 16 March and 9 April, and from CAN (2.96 t ha^{-1}) when 50 kg was applied on each of the four dates.

Neither the form nor timing of N had any effect on the oil content of the seed; however, Mikado contained more than Ariana, 49.1 and 45.7% oil in dry matter respectively. (Darby and Hewitt)

The efficiency of conversion of radiation to dry matter. The development of the oilseed rape canopy progresses through three distinct phases: (1) the vegetative canopy of stems and leaves (2) the flowering canopy of stems and leaves plus a large area of highly reflective yellow petals and (3) the reproductive canopy of stems and growing pods. Each canopy potentially has different photosynthetic characteristics, affecting the efficiency with which incident photosynthetically active radiation (PAR) is converted to dry matter. This was examined in crops grown in multifactorial rape experiments in 1985 and 1986. The mean efficiencies of use of PAR during the vegetative, flowering and reproductive phases were 2.5, 1.0 and 2.1 g dry matter MJ^{-1} in 1985 and 2.3, 1.1 and 3.3 g MJ^{-1} in 1986. The cause of the difference in efficiency in the post-flowering period in the two years is not known.

In 1985, measurements with a spectroradiometer showed that 60% of the incident radiation was reflected back to the sky by the flower canopy at maximum flowering. The recalculated conversion coefficient for the green canopy during the flowering period was 3.0 g MJ^{-1} PAR, comparable with the values during the pre- and post-flowering phases. This implies similar photosynthetic efficiencies for the various vegetative and reproductive structures. Much of the green leaf area was lost during flowering. If more had been retained, greater assimilate production and retention of pods might have resulted, though the scope for further increase is limited because radiation interception by the pods and stems at the end of flowering was generally around 90%. (Leach; Pearman and Rainbow)

Sugar beet

Predicting the N fertilizer requirement of sugar beet. The ability to give specific recommendations on the amounts and timing of N applications, tailored to individual fields, depends in part upon knowledge of how much mineral N the soil contains in spring. An assessment of the value of the Soils Department's nitrate leaching/mineralization model to predict spring N from autumn measurements (*Rothamsted Report for 1986*, 48) has now been made in two years and for 23 sites.

Particle size distributions and bulk densities were measured for each soil to calculate volumetric moisture/suction pressure relations (Hall, Reeve, Thomasson & Wright (1977) *Water retention, porosity and density of field soils*, Soil Survey Technical Monograph No. 9). Use of the measured values, instead of estimates based on qualitative descriptions of soil texture, improved the model's performance. For mineral soils which had received no organic manures (representing over 60% of the national sugar-beet acreage), predictions of soil mineral N at drilling were, in most cases, within 15 kg ha^{-1} of measured values in both years. Predictions were less precise for organic soils and mineral soils that had received organic manures. This was partly because information on the rate, time of application and N content of such manures was inadequate, and also the effect of any errors in estimating mineralization of organic matter.

In the wet spring of 1987 there was much concern, especially in the West Midlands, that the application of compound fertilizers well before drilling might have led to excessive amounts of nitrate being leached. Use of the model indicated that this concern was probably justified, because in simulations most of the N applied before mid-March on light soils in the West Midlands was leached out of the top 90 cm of the soil. In simulations for texturally similar soils in East Anglia, much of the N remained available to crops because rainfall was less than in the West Midlands. (Pocock; Millichip with Jaggard, Broom's Barn and Dr. M.J. Armstrong, British Sugar)

Nitrogen and the quality of sugar beet. The commercial extraction of sugar is impaired by large concentrations of a amino-N compounds in harvested beet. Data from a series of N response experiments on a wide range of soil types and during many seasons were used to examine the accumulation of these compounds, in relation to N supply, uptake and distribution within the plant.

Amino-N concentrations in the storage roots increased with the N content of the whole plant, especially when uptakes were greater than 200 kg N ha^{-1}. Differences in soil type had a larger effect on concentrations than did the amount of fertilizer N at an individual site. Variation between sites was not attributable simply to differences in N supply, as indicated by the uptakes of unfertilized crops; differences in timing of uptake, especially during the later stages of growth, in the partitioning of N between shoot and storage root and in the partitioning within the storage root between amino-N and other nitrogen compounds all contributed to the variation. (Milford and Pocock)

Modelling dry matter partitioning in sugar beet. A model of dry matter partitioning in sugar beet has been developed to describe the dynamics of partitioning between shoot and root. The partitioning process is defined as $dR(t)/dW(t)$ where $R(t)$ and $W(t)$ denote respectively the root and total dry weights t days from sowing. An algorithm was devised to estimate the local dynamics of partitioning under the constraints that dR/dW starts from zero, is monotonically increasing and does not exceed unity.

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In all crops analysed the main features of partitioning could be represented by a linear increase in dR/dW up to a saturating value close to unity. Two parameters define this representation: the time when the partitioning to the root begins and the rate at which partitioning increases with time. Using thermal time above a base temperature of 0°C reduced the coefficient of variation of the intercept with the time axis from 43% to 28% and of the rate of increase in dR/dW from 40% to 25%. Fixing the intercept at 300°Cd further reduced the coefficient of variation of the rate of increase to 15%. In some crops the constraint that dR/dW cannot exceed unity needs to be relaxed to accommodate a significant decline in shoot dry weight, for example under conditions of prolonged water stress. (Chalabi, Day and Milford)

Sunflower

Photosynthesis and effects of water stress. In the conditions of southern Spain, sunflower hybrid SH3622 achieves greater production of dry matter than the hybrid Sungro 380. The physiological and biochemical processes in photosynthesis which may be responsible for this difference are being examined. When grown with ample water and nutrients, the maximum rate of photosynthesis in saturating CO_2 and light was greater in SH3622 than in Sungro 380, though carboxylation efficiency was similar in both. Efficiency of light utilization was slightly greater in SH3622 than Sungro 380. Under these optimum conditions for photosynthesis, stomatal conductance, protein and chlorophyll contents and amount and activities of Rubisco per unit area of leaf were similar, but SH3622 had more, smaller cells per unit of leaf area. There was no difference in the catalytic response of Rubisco to CO_2 and O_2. Water stress, developed over a few days, decreased both carboxylation efficiency and maximum rates of photosynthesis rather more in SH3622 than in Sungro 380. This decrease was not related to differences in tissue water content or turgor at a given water potential. Stress decreased the activity of Rubisco per unit area of leaf. (Gimenez, Lawlor, Ward and Young; Mitchell with Keys, Biochemistry)

The development of sunflowers under UK conditions. Timeliness of flowering and earliness to maturity will be crucial to the acceptance of sunflowers as a major alternative arable crop, but most currently-available cultivars have been selected in the warmer conditions of more southern latitudes.

A preliminary experiment indicated that the development of one of the shorter and potentially early-maturing cultivars, Asmer 3, is responsive to changes in daylength. Plants sown before the beginning of May produced fewer leaves and flowered earlier than later sowings. As a result they were shorter (94 cf. 135 cm) and had less total dry matter and slightly smaller heads. Similar results were obtained with the taller cv. Cerflor. Results so far suggest that there may be a decrease in yield associated with earliness to maturity. (Milford; Mullen, Rainbow and Stevenson)

General physiological studies

Biomass production at low temperatures. The physiological and biochemical processes determining biomass production at cold, but not freezing, temperatures are being studied in a wide range of crop plants, including varieties of wheat, sunflower and oilseed rape.

Photosynthesis of spring (cv. Highbury) and winter wheat (cv. Avalon) has been measured for plants grown at 6°C or at 25°C and following short term transfers between these temperatures. Lower rates of photosynthesis in the cold were related to smaller stomatal conductance and to metabolic limitations, but Rubisco activation *in vivo* was large suggesting that control operates on other processes at low temperatures. When assimilation of plants that had been grown at 6°C was measured at a wide range of temperatures (whilst maintaining

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constant CO_2 partial pressure in the leaf) Avalon but not Highbury suffered an almost complete inhibition of photosynthesis above 25°C. Plants kept at 25°C overnight had substantially (+ 40%) larger photosynthesis and greater *in vivo* activation of Rubisco. Inactivation of Rubisco at high temperatures may limit assimilation in warm conditions for winter wheat grown at chilling temperatures. (Ward and Lawlor; Plumb and Young with Keys, Biochemistry)

Spatial and temporal patterns of growth in leaves and other organs. When fertilizer N is applied to winter wheat crops, leaf sizes increase more through increases in cell numbers than in average cell sizes (*Rothamsted Report for 1986*, 49). Studies of the influence of N on spatial and temporal patterns of growth, cell division and cell size within leaves can elucidate the mechanisms. Methods are available for measuring each of these quantities: cell size distributions can be measured using the Coulter counter (*Rothamsted Report for 1985*, 67-68), patterns of cell division can be estimated using mitotic indices, and patterns of growth can be obtained from marking experiments. Simple arguments based on conservation of cell numbers show that these patterns are interrelated in such a way that if any two can be measured, the third can be calculated but all these methods are laborious and time-consuming. Amongst simpler methods, one promising approach is to estimate the pattern of growth directly from patterns of cell size using equations derived from the continuity equation for cell number density. This approach can be used in simple organs like wheat leaves, where growth occurs mainly by elongation in one dimension. Theoretical investigations are now underway to extend this method to growth in two and three dimensions. (Gandar and Chalabi)

Splash and droplet dispersal

Canopy measurement using a laser scanner. An optical scanner is being developed to provide rapid but detailed geometric information on crop canopies. This information is required when using the simulation algorithm to estimate heavy particle dispersal and deposition rates in crop canopies. The scanner measures impact probability directly by detecting the intersections of a narrow collimated beam of light passing through the crop canopy. This information can be used to calculate crop area density, the angle and area index of crop elements and other geometric parameters. Such information may also be valuable in studies of photosynthesis and crop growth. (Walklate)

Dispersal of splash-borne pathogens. The height and distance travelled by splash droplets is largely determined by the size and velocity of the impacting raindrop (*Rothamsted Report for 1986*, 52). A relationship between maximum splash height and raindrop size has been established and used, in conjunction with an empirical model of raindrop size distributions, to examine the relationship between the vertical transport of splash droplets and rainfall intensity. The calculations suggest that rainfall intensity will be a poor indicator of periods of vertical splash dispersal and that a rain intensity index based on the proportion of raindrops greater than a threshold diameter would be more useful. Such an index could be derived from radar reflectance measurements of rainfall, given some additional automatic monitoring of rain splash, and may have considerable potential for country-wide forecasting of disease spread. (Walklate and McCartney)

Deposition and dispersal of agricultural sprays. A spinning disc atomizer, mounted on a trolley that traverses a trackway placed at crop height, has been developed for investigations of the effects of weather and drop size on the fate of spray drops. Downwind dispersal of spray has been measured in experiments in which wind and temperature profiles and atmospheric turbulence were monitored. The spray plume could be traced to at least 20 m downwind of the sprayer even in very light winds.

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In studies of the dispersal of 60 μm droplets, inertial impaction was probably the dominant mechanism for particle deposition at distances greater than 2–3 m from the source. Even in light winds, droplets were rapidly dispersed upwards; for example, at 10 m from the source, droplet concentration 3 m above the crop was often more than 50% of that at the top of the crop. (Macdonald, McCartney and Walklate; Croft)

Plant composition and nutrient uptake

A nitrate/proton symport at the tonoplast? Previously we reported that we were unable to find any evidence for a nitrate/proton symport in tonoplast vesicles when using quinacrine as a pH probe, but results obtained with acridine orange were consistent with the presence of this transport system (*Rothamsted Report for 1986*, 153). This has been investigated further and the results showed that acridine orange altered the response to anions of both ATP and inorganic pyrophosphate-dependent pH gradient formation in tonoplast vesicles from oat (*Avena sativa* L.) roots and red beet (*Beta vulgaris* L.) storage roots. When used as a fluorescent pH probe in the presence of I^-, ClO_3^-, NO_3^-, Br^- or SCN^-, acridine orange reported lower pH gradients than either quinacrine or [^{14}C]methylamine. Acridine orange, but not quinacrine, reduced [^{14}C]methylamine accumulation when $NO_3^-$was present indicating that the effect was due to a real decrease in the pH gradient, not a mis-reporting of the gradient by acridine orange. Other experiments indicated that acridine orange and NO_3^- increased the rate of pH gradient collapse both in tonoplast vesicles and in liposomes of phosphatidylcholine, and that the effect on tonoplast vesicles was greater at 24°C than at 12°C. It appears that acridine orange and certain anions increase the permeability of membranes to H+ probably because protonated acridine orange forms a lipophilic ion pair with some anions and this ion pair is able to cross the membrane of the vesicles thus dissipating the pH gradient (Garlid & Nakashima, *Journal of Biological Chemistry* (1983) **258** , 7974-7980). We have concluded that the published evidence for an NO_3^-/H^+ symport involved in the export of NO_3- from the vacuole (Blumwald & Poole, *Proceedings of the National Academy of Sciences, USA* (1985) **82** , 3683-3687) is an artefact caused by acridine orange. These effects of acridine orange clearly show the dangers of trying to use pH probes to study the linkage between proton pump activity and anion transport. (Pope and Leigh)

Integration of whole root and cellular hydraulic conductivities in cereal roots. The hydraulic conductivities of excised whole root systems of wheat (*Triticum aestivum* L. cv. Atou) and of single excised roots of wheat and maize (*Zea mays* L. cv. Passat) were measured using an osmotically induced back-flow technique. Ninety minutes after excision the values for single excised roots ranged from 1.6×10^{-8} to 5.5×10^{-8} m s^{-1} MPa^{-1} in wheat and from 0.9×10^{-8} to 4.8×10^{-8} m s^{-1} MPa^{-1} in maize. The main source of variation was a decrease in the value as the length of excised root on which the measurements were done increased. The hydraulic conductivities of whole root systems, but not of single excised roots, were smaller 15 h after excision. This was not caused by occlusion of the xylem at the cut end of the coleoptile.

The hydraulic conductivities of epidermal, cortical and endodermal cells were measured using a pressure probe. Epidermal and cortical cells of both wheat and maize roots gave mean values of 1.2×10^{-7} m s^{-1} MPa^{-1} but in endodermal cells (measured only in wheat) the mean value was 0.5×10^{-7} m s^{-1} MPa^{-1}. These cellular hydraulic conductivities were used to calculate the root hydraulic conductivities expected if water flow across the root was via transcellular (vacuole-to-vacuole), apoplasmic or symplasmic pathways. The results indicated that, in freshly-excised roots, the bulk of water movement is unlikely to be via the transcellular pathway. This is in contrast to our previous conclusion (Jones, Leigh, Tomos & Wyn Jones, *Planta* (1983) **158**, 230-236) which was based on hydraulic conductivities of whole root systems

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of wheat measured 14–15 h after excision and which were probably artefactually low. We now conclude that, near the root tip, water flow could be through a symplasmic pathway in which the only substantial resistances to water flow are provided by the outer epidermal and the inner endodermal plasma membranes. Further from the tip, the measured hydraulic conductivities of the roots are consistent with flow either through the symplasmic or apoplasmic pathways (H. Jones, SERC/CASE student and Leigh with Dr A.D. Tomos and Prof. R.G. Wyn Jones, University College of North Wales, Bangor)

Straw incorporation

Methods of alleviating the adverse effects of straw. More farmers are beginning to incorporate surplus straw into the soil rather than burn it. Ploughing in straw to 15 cm or more does not normally decrease yield by more than about 5% of that where straw is burnt, although losses are larger where straw remains on the surface or is only shallowly incorporated.

On a Lawford series soil at Northfield in Oxfordshire different systems of straw disposal and cultivation have been evaluated since 1979. The straw treatments are: all burnt, baled leaving stubble, all chopped and spread using a combine-mounted straw chopper. These straw treatments are combined with cultivation treatments which have changed with time. Direct drilling and minimum cultivation (5 cm) have been tested on the same plots since the start. Since then additional depths of tillage have been included; in autumn 1982 to 10 cm, which was deepened to 15 cm in 1984 when an additional depth of 25 cm was added. At this time, ploughing replaced tine cultivation to achieve better straw burial.

In 1987, the best yield, 7.2 t ha^{-1}, was after burning and direct drilling. All ploughing treatments, irrespective of depth, and the presence or absence of incorporated stubble or straw gave yields averaging 5.5 t ha^{-1}, not significantly different from one another. Unlike 1986 direct drilling into chopped straw yielded well, 6.2 t ha^{-1}, which was better than the yield on ploughed land. The direct-drilled crop stayed green longer than that after ploughing, and although relevant data are not yet available, this may be related to take-all which appeared patchily throughout the experiment.

Direct drilling or shallow cultivation after burning have most frequently given the best yields, but when chopped straw was present the yields have been among the smallest in the experiment. In autumn 1986, the straw on one-half of each of the plots on which chopped straw had been returned for seven years was burnt and this removed the fresh straw and much of the partly decomposed residues that remained from previous crops. These plots were then direct-drilled or ploughed to 5, 15 or 25 cm. Average yield was 6.4 t ha^{-1} which was about 0.8 t ha^{-1} larger than where chopped straw remained. On direct-drilled land, although yield improved compared with chopped straw plots it was still 0.5 t ha^{-1} less than on plots after eight years of burning.

Another problem facing the farmer who incorporates straw is that of volunteers in the following crop, especially where straw remains on or near the soil surface. In one treatment the number of fertile ears derived from volunteer plants reached 27% of the total. This degree of contamination was decreased by about 50% by deeper ploughing, however the best control was obtained by a combination of burning and cultivation. (Christian and Bacon with Pulford, sandwich student)

Effects of different amounts of straw. Combine-mounted straw choppers, particularly those on harvesters with wide tables, fail to spread straw satisfactorily and chaff is often concentrated in a narrow band behind the combine. The increased amounts of chaff and straw may lead to poor growth in stripes. At Northfield the effects on the following wheat crops of 0, 5, 10, 15, 20 t ha^{-1} per year of chopped straw added cumulatively and incorporated to 15 cm

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have been tested for four years. Similar experiments were started this year at Rothamsted and Woburn where straw loadings up to 23 and 17 t ha^{-1} respectively were applied.

At every site early growth was depressed by the incorporation of straw. Nevertheless compensatory growth was made in the spring, and at harvest there were no significant differences in yield, which averaged 7.5 t ha^{-1} at Northfield, 4.8 t ha^{-1} at Rothamsted and 2.8 t ha^{-1} at Woburn. At Rothamsted and Woburn yields were poor, the harvest index was only about 35%, probably caused by take-all infection. (Christian and Bacon with Pulford, sandwich student)

Straw disposal before winter oilseed rape. The experiment described last year (*Rothamsted Report for 1986*, 157) was repeated but tested simpler treatments. Straw disposal was by either burning; or chopping and spreading; or baling. For each of these treatments the soil was then either tine cultivated or ploughed. Oilseed rape, cv Bienvenu, was sown at 8 kg ha^{-1} on either 20 August or 5 September, with either none or 50 kg N ha^{-1} applied on 18 August to the seedbed.

Plant counts on 26 September (early sown) and 31 October (later sown), showed that the rape established well (mean population 99 plants m^{-2}) and numbers were not significantly affected by any of the treatments. Unlike 1986 when many plants were killed during winter, counts in March showed that only 14 plants m^{-2} were lost, which left an adequate number to ensure that yield was not affected by plant population. Winter losses were not significantly affected by treatments but tended to be larger when later- sown rape had to compete with volunteer barley in stale tine-cultivated seedbeds.

The average seed yield, 3.69 t ha^{-1} (90% DM), was not significantly affected by either straw or cultivation treatment. The application of seedbed N increased yield by 0.21 t ha^{-1} and sowing in August by 0.27 t ha^{-1}. The mean oil content, which was not affected by straw or cultivation treatment was 47.6% oil in dry matter. Oil content was increased by sowing in August by 0.8% and by 0.2% by the application of seedbed N. Oil yield was similarly affected, August and September sown crops yielded 1652 and 1510 kg respectively and the application of seedbed N increased yield by 98 kg oil ha^{-1}. (Darby)

Toxin production and oxygen demand. Effects of straw incorporation were investigated in small lysimeters 1 m deep incorporating topsoil and subsoil horizons from two sites, a clay soil from Northfield and a sandy loam from Woburn. Soil water potential was kept at -20 kPa using constant-head devices linked to tensiometer cups. The equivalent of 20 t ha^{-1} straw was either placed on the soil surface or incorporated in the top 10 cm of soil. Straw on the surface delayed emergence, the time for 50% seed emergence increased from 5.7 to 8.2 days without and with straw respectively. Adding nitrogen fertilizer to the surface straw further delayed emergence on the clay but not on the sandy loam. The rate of emergence was also somewhat slower when straw was incorporated on both soil types but adding nitrogen to the straw overcame the delay.

At harvest surface straw had no effect on grain yield but incorporation reduced yield by about 20% because ear numbers were decreased due to fewer tillers producing fertile ears. Nitrogen again overcame this effect. The addition of straw to the soil did not significantly improve the aggregate stability of the sandy loam soil and as water supply was controlled throughout the experiment the reason for effects of straw being greater in the clay soil needs further investigation. (Goss, Smallfield and Harper)

Plant growth and take-all

The relationship between take-all rating (TAR) and yield of field crops and the effects of soil nutrient status on disease levels have been extensively studied, but little is known about

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how and when diseased root systems fail to meet the needs of the plant. Root and shoot growth, and water and nutrient uptake in relation to TAR have been studied in a growth room experiment.

Eighteen-day-old winter wheat seedlings (one per pot) were transplanted into sterilized soil over a disc of agar culture of the take-all fungus. Within ten days, water use was drastically decreased although there were no differences in root and shoot weights compared with the controls. Infected plants started to wilt two days later, when TAR was 1 and 5 of 11 root axes (controls had 8 axes) were lesioned and 6% of the total root length blackened. (This, and all following data are per plant, the average of four replicates). By day 17, shoot dry matter (DM) was just 60% of the control, the TAR had risen to 2, and only five axes and 9 m of root were healthy. At this stage, controls had 14 axes and 26 m of root. Infected plants continued to grow very slowly, using only 1–2 g d^{-1} of water compared to 20-30 g d^{-1} used by the controls, and by day 38 the DM in the shoots of infected plants was only one-third of that in the controls. By then TAR was 3, 18 axes out of 21 had lesions and although 13 m of a total of 18 m of root appeared normal, much of this length was distal to lesions and it is not known what proportion was functional. At this time the controls had 30 axes and 101 m of root.

The experiment ran for 46 days when infected plants had produced only two to three visible tillers and 21 root axes compared to the 12 tillers and 30 axes on control plants. Shoot N concentrations were always less in infected plants whilst concentrations in roots were always greater, reflecting the impaired translocation of N from roots to shoots. Both reduced shoot N concentration and transpiration rate in the infected plants preceded the appearance of visible symptoms and occurred even at low TAR. (Barraclough; Haynes with Hornby and Hodnett, sandwich student, Plant Pathology)

This year on the Farms

Weather

The season was difficult with extremes of weather. January was one of the coldest for many years with 25 ground frosts and temperatures of −10°C. February and March were milder and drier than usual and most of the spring drilling was completed by the end of March. The first half of April was very wet but was followed by a dry period with the highest temperatures for 40 years in which potatoes were planted in ideal conditions. May was wetter than average and very windy which hindered the application of weedkillers. June was also wet but a dry spell in early July enabled the small area of hay to be made in good order before wet weather returned.

Grain harvest started at the beginning of August but was interrupted by rain and delayed by late ripening of much of the wheat. Cereal harvest finished on 17 September at Rothamsted and 24 September at Woburn. The quality was generally poor, particularly of the wheats and much drying was needed.

The start of the autumn sowing programme was delayed by the late harvest and by problems in straw disposal. Little could be burnt, much of the wheat straw broke up badly so most was chopped and incorporated. October was an appalling month with over three times the average rainfall and much flooding seriously delayed autumn work.

Crops and experiments

Of the 335 ha farmed (259 ha at Rothamsted and 76 ha at Woburn) cereals occupied 186.6 ha, potatoes, beans and oilseed rape a total of 53.4 ha. The remainder was grass, fallow and small areas of sugar beet, sunflowers, maize, peas, lupins and for the first time linseed.

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Wheat. All was autumn-sown with 80.2 ha at Rothamsted and 24.8 ha at Woburn. The main cultivars were Avalon and Mercia.

Crops looked poor after the very cold January and wet spring. Appearance improved subsequently but yields were less than last year, particularly of crops following another cereal as take-all was severe. Crops after cereals were given prochloraz and carbendazim ('Sportak Alpha') to control eyespot. Leaf diseases were few and a second fungicide spray was delayed, partly by bad weather, until ear emergence when propiconazole ('Tilt') and carbendazim plus maneb ('Septal') were applied to most crops.

Cereal aphids were few and did not warrant spraying. In an experiment testing repeated aphicide sprays yield was not increased significantly. Some crops at Woburn suffered an unusual and damaging attack by the stem borer *Opomyza*.

In the third year of the long-term straw incorporation experiment (p. 25) at Rothamsted the mean yield of the fourth cereal, cv. Mission, was only 5.9 t ha^{-1} compared with 8.3 t ha^{-1} last year. At Woburn the mean yield was only 4.1 t ha^{-1} compared with 7.5 t ha^{-1} last year.

In experiments comparing cultivars at Rothamsted after a two-year break and after wheat mean yields were about 1.5 and 1.0 t ha^{-1} less respectively than last year. After the break Hornet, Brimstone and Rapier were best with yields of 9.5 t $^{-1}$. After wheat Hornet was also best with a yield of 9.2 t ha^{-1}, closely followed by Galahad with 8.9 t ha^{-1}.

Squarehead's Master was reintroduced to Broadbalk for the first time since 1967, on the continuous wheat section given no agrochemicals other than weedkiller, to compare with the current modern cultivar Brimstone. The work was initiated at the request of the Institute of Plant Science Research, Division of Cytogenetics and Plant Breeding to determine the extent to which modern yields depend on the use of nitrogenous fertilizer or on the use of modern varieties. The total above-ground dry matter produced by both cultivars was similar at all rates of nitrogen. From small areas in which lodging was physically prevented Brimstone gave 40% more grain than Squarehead's Master; this increased to more than 100% at the highest rates of nitrogen when lodging was not prevented. The best yields of Brimstone came after the two-year break, 9.4 t ha^{-1} from the plot given farmyard manure, 9.3 t ha^{-1} from the fertilizer plot given most nitrogen.

Barley. There were 39.9 ha of winter barley and 37.6 ha sown in spring. The main winter-sown cultivars were Igri and Magie. Most followed a cereal and therefore was sprayed in spring with prochloraz and carbendazim ('Sportak Alpha') against eyespot. A further spray of triadimenol ('Bayfidan') was applied at ear emergence. Harvesting was completed on 8 August, just before the weather broke.

The variety on the Factors Limiting Yield experiment (p. 17) was changed from Panda to Magie to study the effects of treatments on malting quality as well as yield. Following oats a mean yield of 6.7 t ha^{-1} was obtained, 5.2 t ha^{-1} following barley, both about 1.0 t ha^{-1} less than last year.

An early-sown experiment showed an increase of yield from 4.2 t ha^{-1} to 7.2 t ha^{-1} when volunteers were controlled but no benefit from the use of autumn insecticides. In an experiment comparing cultivars the best were Gerbel, Marinka and Magie with over 8 t ha^{-1}, outyielding Igri which gave 7.3 t ha^{-1}.

Spring barley, mostly Klaxon, was sown in good conditions. Triumph was retained on Hoosfield and gave up to 6.3 t ha^{-1} with fertilizers alone, 5.9 t ha^{-1} with farmyard manure alone and 6.1 t ha^{-1} with the combination of farmyard manure and 48 kg N ha^{-1}.

A spring cultivar experiment gave a mean yield of 6.8 t ha^{-1} at Rothamsted, 5 t ha^{-1} on the light land at Woburn. Best yields came from Regatta, Cameo and Doublet at Rothamsted, Digger, Regatta and Doublet at Woburn. In the Ley Arable experiment at Woburn Klaxon

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gave some yields exceeding 7 t ha^{-1}; the best yields came where long leys had been included in the rotation.

Triticale and rye. Small areas were grown at both farms in experiments including other cereals to compare yields with differing inputs. This year triticale gave the smallest yields in contrast to last year when it gave the best. At Rothamsted the mean yields of Panda barley, Avalon wheat and Dominant rye were all about 6.4 t ha^{-1}, Status and Lasko triticale gave 5.9 and 5.2 t ha^{-1} respectively. On a very sandy site at Woburn the barley yielded 6.4 t ha^{-1} and the rye 6.0 t ha^{-1}, the wheat gave only 4.2 t ha^{-1}, Status and Lasko triticale yielded 4.6 and 4.1 t ha^{-1}.

Oats. There were 16.1 ha grown as a break crop, 12.1 ha were autumn-sown Bulwark, the remainder spring-sown Rollo and Dula.

Beans. There was only a very small experimental programme. Because seed arrived late there were only 3.5 ha of winter beans, cv. Bourdon, and these were broadcast and ploughed in on 12 November.

The biggest effect on yield was from seed rate and this confirmed earlier work done on differing sowing dates. The mean yield was 3.1 t ha^{-1} from 12 seeds m^{-2} and 5.2 t ha^{-1} from 36 seeds m^{-2}. At the heavier seed rate fungicides increased yield by just over 1.0 t ha^{-1} but had less effect at the lighter seed rate.

There were 7.4 ha sown in spring, mostly Minden. In an experiment comparing cultivars, row spacing and pathogen control there was little difference between 12 cm and 48 cm rows but full pathogen control increased the mean yield from 3.5 t ha^{-1} from untreated plots to 4.9 t ha^{-1}. The cultivar Alfred gave the best mean yield of 4.9 t ha^{-1}, Minden 4.4 t ha^{-1} and the early-ripening cultivar Troy 3.8 t ha^{-1}. Alfred with full pathogen control—two sprays of deltamethrin ('Decis') in spring followed by one of chlorothalonil ('Rover 500') and benomyl ('Benlate') with a final one of mancozeb and maneb ('Kascade')—gave 5.9 t ha^{-1}.

All beans were harvested by 25 September following desiccation with diquat ('Reglone') but unusually the spring beans ripened before the winter-sown crop.

Oilseed rape. There were 23.7 ha all grown at Rothamsted except for a very small area at Woburn grown for work on fertilizer N efficiency. Except for 1 ha all was autumn-sown following barley or wheat. Most was cv. Bienvenu but 9 ha of cv. Ariana were sown for work on the effects of harvesting methods on glucosinolate content.

Volunteer cereals were controlled with TCA applied pre-sowing and weed control was satisfactory where this was followed by metazachlor ('Butisan S'). Where clopyralid and propyzamide ('Matrikerb') were used weed control was less good, particularly of cleavers.

Although direct combining, following desiccation with diquat ('Reglone'), did not start until 5 August because of bad weather some reasonable yields were obtained despite shedding. On the Factors Limiting Yield experiment (p. 20) Bienvenu gave a mean yield of 4.0 t ha^{-1} compared with Ariana with 3.7 t ha^{-1}. An experiment comparing drills gave a mean yield of 3.7 t ha^{-1}; drilling with a Stanhay precision drill gave slightly better yields than conventional and air-assisted drills but not enough to justify the slower work rate. A large experiment on cv. Ariana compared swathing, desiccation followed by direct combining and combining without desiccation on three dates spanning a normal harvest date. Desiccating early and swathing on 9 July gave poor yields, 1.4 t ha^{-1}, because of long exposure to weather before combining. All the other treatments gave yields of about 3 t ha^{-1} except for the last harvest of the swathed plots which gave only 2.5 t ha^{-1} probably because of the double handling given.

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Outside site

In addition to work at Rothamsted and Woburn farms oilseed rape yields were taken by combine from the Rothamsted experiment on straw incorporation sited at Whaddon (p. 27) and post-harvest cultivations were also done.

Cattle

Ninety-seven yearling steers were bought and 79 were sold fat.

Equipment

An existing barn was converted for bulk grain storage to hold about 300 tonnes.

Staff and visitors

A.E. Johnston was appointed Head of the Soils and Crop Production Division and also Head of the Soils Department on 17th August 1987 and R.A. Leigh was appointed Head of the Department of Crop Production from 1st December 1987.

The Department was saddened by the sudden death of Tony Barnard in February in his 21st year of service.

Staff who retired (and their years of service) include Gillian N. Thorne (38), A.T. Day (37), R. Fearn (21), and R. Gibson (20). Janet Why transferred to the Computing and Electronics Department, G. Catherall retired on health grounds and Fiona Gordon and P.N. Pilgrim resigned.

We welcomed a number of new people, Jacqueline K. Clark, S. Bartholomew, J.T. Bill and A.M. Hunt on the Farm and Kathleen Robinson, C.J. Hall and Helen Weir. Jane Fieldsend and Andrew Porter were appointed to study the effects of husbandry practices on the glucosinolate content of oilseed rape, both funded by a MAFF Open Contract. David Ward will work on the effects of low temperatures on growth and biomass production, funded by the EEC Non-Nuclear Energy Programme. Lindsey Smith, who has since been awarded a Ph.D. by Wye College, arrived to study leaf and canopy growth in sugar beet funded by the Sugar Beet Research and Education Committee (SBREC).

R.A. Leigh spent February and March in the laboratory of Dr Marty, Institute de Biologie Cellulaire, Université d'Aix-Marseilles, Marseilles, France, studying transport systems at the tonoplast and in July he presented a paper at the annual meeting of the American Society of Plant Physiologists in St Louis, USA and visited laboratories there. D.W. Lawlor attended an EEC conference 'Biomass for Energy and Industry' in Orléans, France in May and another conference on 'Improving winter cereals for temperature and salinity stress', organized by the Spanish National Institute of Agricultural Research and the International Centre for Agricultural Research in Dry Areas (ICARDA). R.D. Prew visited France in October as a member of an AFRC/ADAS team looking at straw disposal problems.

Dr P.W. Gandar of DSIR Palmerston North, New Zealand came in August to work on aspects of plant process modelling and Dr Carmen Gimenez of the University of Cordoba, Spain, in May to work on photosynthesis and effects of water stress.

Visitors. In total about 107 programmes were arranged for about 1000 visitors. As usual about a third came from overseas but the proportion of farmers increased slightly to about a quarter.

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