Report for 1978 - Part 1

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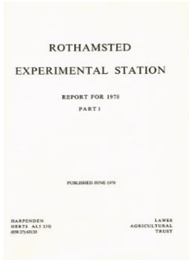
ROTHAMSTED

EXPERIMENTAL STATION

REPORT FOR 1978

PART 1

Physics Department

T. Woodhead

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Introduction

For the Physics Department, 1978 saw the successful conclusion of many researches, and the initiation of new ones. A long and careful series of irrigation experiments was completed on the Rothamsted silty clay loam, and the measurements were analysed in conjunction with those from the Woburn experiments on a light loamy sand soil (Penman, *Rothamsted Report for 1970*, Part 2, 147–170) to give a new set of data and concepts that can readily be applied in farm irrigation. The responses to drought of spring barley, that were measured in 1976 using mobile rain shelters, have been fully analysed and reported; the findings have been embodied in a promising new physical model that describes the effect of drought on light interception, photosynthesis and respiration and that indicates the extent to which dry matter accumulation is affected by drought-induced changes in these processes. Soil structure, and its measurement, have been studied collaboratively by the Rothamsted Soil Structure Working Group since 1975, and the findings of the first phase of the collaboration will be published in 1979 as a set of seven contiguous papers, of which the Physics Department contributed three. Some of the resources that were devoted to the irrigation experiments, together with some new resources of manpower and equipment, have been deployed in new studies of the movement and deposition of cereal disease spores. New facilities for studies in soil water physics were installed during the year in a purpose-built laboratory, allowing a resumption of research into soil water movement and drainage formerly undertaken by the ARC Unit of Soil Physics at Cambridge and interrupted when the Unit's staff transferred to Rothamsted in 1977. Other resources, new and existing, are being directed to the Little Knott mobile shelter site where, in support of the continuing and expanding programmes of drought and tillage research, a new computer-controlled data acquisition system will be commissioned in spring 1979. Roots, responsive though they are to both tillage and drought, have been little studied at Little Knott because the smallness of the plots there, and the need to reuse them in successive years, do not allow sacrifice of soil in root excavations. In collaboration with the Botany Department, a non-destructive method

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for root observation is now being evaluated: transparent tubes have been inserted into a field soil, and roots, as they contact the tube walls, have been observed and photographed from above ground by means of light pipes. It is likely that this technique will prove useful in comparative, if not absolute, determinations of root densities.

Other developments and testings of new equipment and techniques have featured prominently in the Department's 1978 programme, and have been much aided by the facilities and expertise that are available in the new departmental workshop. For projects in soil water physics, a prototype apparatus has been built that will permit measurement of hydraulic conductivity in swelling soils; and to help studies of water movement in heterogeneous soils, a new system is being constructed that allows the switching between several tensiometers of the hydraulic connection to a single pressure transducer. The designs and construction of a portable photosynthesis/transpiration chamber and a portable gas mixing apparatus were described in *Rothamsted Report for 1977*, Part 1, 202. The chamber has an exciting potential for use in various studies of photosynthesis, and, in exploitation of this potential, several chambers have now been constructed, some to modified designs that suit particular applications. The gas-mixing apparatus has been developed to the stage that it is now marketed by a local manufacturer; its key component is an orifice plate, and the characteristics of the flows through such orifices, for various diameters and at various gas pressures, have been measured and analysed. A new Rothamsted wind tunnel, which will support the laboratory phases of research into the movement of cereal disease spores, has undergone acceptance trials throughout the year. Control of air humidity is not yet adequate, but air temperature and wind speed are sufficiently controlled that some experiments can be undertaken.

On the Little Knott mobile shelter site, where birds severely damaged 1978s emerging barley crop, opportunity was taken to field-test new procedures for measuring leaf extension and photosynthesis and to gather experimental data that will be used in the development of physical models of plant response to drought. In preparation for a drought experiment in 1979 and a tillage experiment in 1979/80, new ducting has been laid through which to route signal cables, portable covers have been built so that soil adjacent to the sheltered areas can be protected from the winter rains, additional defences have been erected against birds and vermin, and a deioniser has been installed so that nutrients can be removed from the irrigation water. Improvements have been made to the purpose-built tillage implements, and in order that cultivations may be carried out in all weathers, a manoeuvre area has been constructed that allows a tractor and implements to be driven to any of the concrete tillage tractor-ways under any state of soil wetness.

The Department was pleased to help entertain and advise, during the year, the Soil and Water Management Association and the Water Inquiry Panel that was appointed by the Minister of Agriculture to review the national need for irrigation water. Within Rothamsted, we have enjoyed active collaborations in soil structure research with the Departments of Soil Microbiology and Soils and Plant Nutrition and the Soil Survey of England and Wales, in irrigation, drought and root studies with the Departments of Botany, Nematology and Soils and Plant Nutrition and the Field Experiments Section, and in aerobiological research with the Department of Plant Pathology.

Agricultural Meteorology

Irrigation and crop growth

Farm crops: yield responses and limiting soil water deficits. Advice to British farmers on irrigation has its scientific base in the irrigation experiments that were conducted between 1951 and 1968 on the light loamy sand soil at Woburn by H. L. Penman (*Rothamsted Report for 1970*, Part 2, 147–170). A complementary series of experiments was conducted between 1964 and 1976 on the heavier silty clay loam at Rothamsted.

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The Rothamsted results have now been analysed to give a comparison, for five crops that were common to both the Woburn and Rothamsted experiments, of the responses to irrigation on the two soils. These responses were measured in terms of the limiting soil moisture deficit, D_l, which is the deficit that must be exceeded before any additional plant growth will result from irrigation, and in terms of the incremental gain, k, in crop yield per unit of applied water. Both D_l and k have import for the practice and planning of farm irrigation.

In the Rothamsted experiments, irrigation was applied through oscillating spraylines, and the schedule for fully-irrigated treatments sought to maintain below 30 mm the calculated potential soil moisture deficit. Other treatments received no irrigation or, in some years, partial irrigation in that full irrigation was applied for only the first, or the second, half of the growing season. Responses were measured for spring field beans and spring barley in 6 years each, for maincrop potatoes in 7 years, and for spring and winter wheat in 2 years each.

In only 3 of the 6 years did the grain yield of spring field beans increase by 10% or more in response to irrigation. D_l for beans was 80 mm: this Rothamsted value may be compared with that for Woburn which is probably less than 30 mm. The largest k-value observed at Rothamsted was 0·006 t ha^{-1} mm^{-1} (grain dry matter); 0·014 t ha^{-1} mm^{-1} had been measured at Woburn. The difference in yield responses to irrigation was mainly attributable to the prevalence at Rothamsted between 1965 and 1975 of broad bean stain virus, which reduced yields of both irrigated and unirrigated crops.

For maincrop potatoes at Rothamsted, irrigation increased tuber yields by 10% or more in 3 years out of the 7, and the value for D_l was 85 mm (Penman had deduced 35 mm for the lighter Woburn soil). The highest k-value at Rothamsted was 0·19 t ha^{-1} mm^{-1}, close to the 0·20 t ha^{-1} mm^{-1} observed at Woburn, and at both sites the largest yields were between 40 and 50 t ha^{-1}.

Of the 6 years of spring barley, only 1, 1976, resulted in a yield response to irrigation that exceeded 10%: in the exceptionally dry 1976 the response was 21%. D_l cannot be derived from a single response, but its lower limit at Rothamsted, from 1976, is 100 mm; D_l for Woburn was reported as 40 mm. In 2 years each of spring and winter wheat, yield was slightly depressed by irrigation; it was deduced that D_l for wheat at Rothamsted is 140 mm or more, which contrasts with the 30 mm that was measured at Woburn.

For beans, potatoes and barley, the ratios D_l at Rothamsted to D_l at Woburn are close to 2·5. For the two soils there is a similar ratio, 2·3, between the amounts of water held in the top metre between the water potential limits of $-0{\cdot}1$ and -15 bar. This finding is important because it suggests that it is possible to predict, for any crop whose D_l is known from either the Woburn or Rothamsted experiments, the corresponding D_l on some other soil provided only that the available water holding capacity of the latter soil be known or measured.

A subsidiary objective of the Rothamsted experiments was to determine whether, and at what growth stage, there might exist critical periods during which the plants were particularly sensitive to drought. No such periods were observed—but the tests were not so sensitive on Rothamsted soil as they would be on soils of lower water holding capacity. However, no critical periods were found in a previous experiment, on barley, that specifically aimed to detect them (*Rothamsted Report for 1977*, Part 1, 200). In none of these researches were the plants short of water during germination and emergence: processes that are particularly sensitive to soil water content. The comparison, in the irrigation experiments, of the effects of water deficits in the first and second halves of the growing season suggested that beans and barley were slightly more sensitive to early than to late deficits, probably because the roots exploited a lesser depth of soil in the early period. (Legg, French and Croft)

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Multidisciplinary experiments: spring beans, grass and legumes. *Rothamsted Report for 1977*, Part 1, 123 and 204 described multidisciplinary experiments, at Rothamsted and Woburn, into the causes of variations in yields of spring beans and of grass and legumes. These experiments were continued in 1978, with the following results. At Rothamsted, the maximum potential soil moisture deficit under non-irrigated spring beans was 140 mm; in response to 75 mm irrigation, grain yield (85% dry matter) increased from 5·8 to 6·0 t ha^{-1}. The maximum potential deficits under grass and clover at Rothamsted and Woburn were 160 and 184 mm, respectively; yield increases from 10·6 to 11·2 t ha^{-1} and from 8·3 to 12·0 t ha^{-1} (dry matter) respectively resulted from 175 mm irrigation at Rothamsted and from 230 mm at Woburn. (Legg, with McEwen, Field Experiments Section, and others)

Analysis of micrometeorological records. As was reported in *Rothamsted Report for 1977*, Part 1, 203, micrometeorological analysis has been concentrated on the data that were collected for beans in 1972 and for potatoes in 1973. The objective of the present analyses is to determine values for these crops for the roughness length, z_o, the zero plane displacement, d, and the drag coefficient, c_d. These parameters, and their changes through the growing season, describe the aerodynamic properties of the developing crops. Differences between the parameters derived for each season's north and south plots, irrigated and non-irrigated, give an indication of the effects of water stress on aerodynamic properties, and, under certain circumstances, give also a measure of the interfering influences of nearby obstacles, such as trees, and of discontinuities at plot boundaries, where different crops may abut. A dependence of these parameters on wind speed may indicate that the crop's aerodynamic structure is altered when the plants are bent or deformed by strong winds. Calculations have been restricted, initially, to data gathered when the atmosphere was at or close to neutral thermal stability. For these data, the measured wind speeds were corrected for any temperature deviations from the values expected in exactly neutral conditions, and the wind speed at height $2h$, where h is crop height, was used as the reference speed in the analyses of variations in z_o, d and c_d. To support these analyses, new computer programs, drawing on the GENSTAT package, have been developed to summarise these parameters and their wind-dependence.

For beans (1972) on the north (irrigated) plot, the mean c_d was 0·022 when winds at $2h$ were between 1·5 and 3·0 m s^{-1}. And from 10 June until 31 August, during which time h increased from 0·45 to 1·5 m, each 10-daily mean value for c_d was between 0·021 and 0·023. For the south (non-irrigated) plot, the mean c_d, 0·019, did not differ significantly from that for the north plot; but, possibly because the south plot was nearer to large trees, its c_d-values were much more scattered. For the north plot during this June–August period, 10-daily mean values for d/h ranged from 0·56 to 0·72 around a mean of 0·66; successive 10-daily values often differed with statistical significance, but these differences were probably associated with factors such as prevailing wind direction, and not with changes in the crop's aerodynamic properties. During September the beans shed their leaves, and d/h decreased to 0·50 in 1–10 September and 0·35 in 11–20 September. On the non-irrigated plot d/h declined to 0·4 in mid-August when the plants began to senesce, but although d/h-values were generally more variable, they were of similar trend to those of the north plot.

For potatoes (1973) on the north (non-irrigated) plot, d/h was close to 0·8 for most of the season; on the south plot, closer to the trees, results were very scattered around an improbably low mean of 0·4. Because irrigation had little effect on plant growth in 1973, the differences between the d/h-values for north and south plots cannot be considered to reflect a real divergence of aerodynamic properties.

The dependence of d/h and z_o/h on wind speed was difficult to assess, and is reported

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only for beans. There were suggestions that d/h increased with wind speed between 10 and 30 June, but decreased with increasing wind speed in July and August, and that throughout the season and on both plots, z_0/h decreased slightly as wind speed increased from 1·0 to 4·0 m s^{-1}.

In 1976, data were collected for spring barley. The resulting records of temperature, humidity and wind speed and direction have been calibrated, sorted and merged and are now stored on the Station's ICL System 4 computer. (Legg, Long, Zemroch, Gordon and Strange)

Movement and deposition of disease spores. A new programme of aerobiological research was initiated in 1977 (*Rothamsted Report for 1977*, Part 1, 204). In 1978, effort was devoted to commissioning the new wind tunnel, in which wind speed and turbulence and air temperature, but not air humidity, can now be satisfactorily controlled. New anemometers and drop and spore generators have been purchased, and plans have been prepared for a 1979 experiment in Great Field that will seek to detect electrical charges on spores of barley mildew (*Erysiphe graminis*); such charges, if present, could affect the motions of the spores. (Legg, McCartney and Strange, with Bainbridge, Plant Pathology Department)

Plant physics

Plant response to water stress

A model for yield response: spring barley. The effects on barley yield of droughts of various intensities at different growth stages were investigated in 1976; the grain yields were reported in *Rothamsted Report for 1976*, Part 1, 236, and the effects on the components of yield and on nutrient uptake in *Rothamsted Report for 1977*, Part 1, 200. Further analysis of the yield and growth measurements of that experiment has sought to determine how much of the drought-induced yield loss can be ascribed (i) to a reduction in leaf area, (ii) to increased stomatal resistance, (iii) to a decrease in individual leaf photosynthesis, and (iv) to an increase in respiratory losses.

A model for the total yield, Y, of dry matter (grain, straw and roots) at harvest is proposed:

$$Y = I.P/I.F$$

where I is the total amount of visible radiation intercepted by green foliage, P/I is a variable that is proportional to the efficiency of use of this intercepted radiation, and F is that proportion of total photosynthate that remains at harvest, not lost to respiration. Measurements showed that drought-stressed plants intercepted less radiation than unstressed ones because they had less total leaf area and because they matured earlier; also, there may have been a change in the angle of foliage in stressed plants, allowing more radiation to pass between their leaves without interception. The effects of drought on the ratio P/I were mainly, but not entirely, through differences in stomatal closure. Effects of changes in individual leaf photosynthesis were not detected: the measurements of internal resistance to carbon dioxide transfer, r_c, and of leaf quantum efficiency, ϵ, were of insufficient precision. The respiration losses, R, of the variously droughted crops were calculated through the equation (McCree, *Crop Science* (1974), **14**, 509–514)

$$R = \alpha P + \beta W$$

in which α is supposed constant and β assumed to depend only on temperature, P is the rate of net photosynthesis plus dark respiration, and W is the total dry mass of the plant. The seasonal total of R, and the corresponding F, would be influenced by drought if α or β or the time course of increase of W were so influenced. Experimentally, no

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measurements were taken that could indicate whether α or β was affected by drought; however, allowance was made, through a known temperature-dependence of β, for differences in leaf temperatures caused by the treatments, and for observed differences in the progression of W.

Through the model, which predicted the measured yield losses reasonably well, the interpretation of the drought experiment is that, at any time in the season, if drought reduces yield it does so mainly by causing a reduction in I: for plants droughted from emergence to harvest, the reduction, in comparison to fully watered plants, was 40%. For plants droughted early in their season, the reduction resulted through a decrease in total foliage area, and for plants droughted late, through earlier maturity and senescence. The effects on Y of drought-induced differences in stomatal resistance were much smaller: for no treatment did they exceed 6%. Stomatal resistances did, indeed, show large responses to drought, but these had such short daily and seasonal durations that Y was little affected. Differences in the respiration factors, F, were likewise small: the most droughted plants respired only 7% more than those fully watered—although the possibility remains that drought caused important, but unmeasured, changes in α and β. Individual leaf photosynthesis can be affected also by non-stomatal responses to drought, and it was the estimates for these effects that contributed the major uncertainty to the predicted Y-values: a change in r_c of $1{\cdot}5\ \mathrm{s\ cm^{-1}}$—the standard error of the difference between measurements in 1976—would cause a change of 15% in P. A second drought experiment will be undertaken in 1979, and improved measuring technique and modified treatment replication should help give better values of r_c so that this successful model can be further exploited. (Legg, W. Day and Parkinson, with Lawlor, Botany Department)

Porometer calibration. The construction of a continuous flow porometer, and a comparison of its readings with those of a diffusion porometer, were described in *Rothamsted Report for 1977*, Part 1, 201. A new model of diffusion porometer, built by Messrs T. & J. Crump (Rayleigh, Essex), has been included in a further series of comparisons of the Rothamsted continuous flow porometer and the diffusion porometer (Messrs Lambda Instruments, Lincoln, Nebraska) that was tested last year. The instruments were compared through laboratory calibrations and through measurements on growing leaves in the field and in a glasshouse. In the laboratory comparisons, all three porometers were calibrated using 'Celgard' porous polypropylene film, and the diffusion porometers were, in addition, calibrated using perforated metal plates from the dimensions of which the diffusion resistance can be calculated. The laboratory findings were that, for both diffusion porometers, resistances measured by reference to a perforated plate calibration would be higher than those referred to 'Celgard' calibration, and, for reasons that are not understood, the two instruments differed in their value for this disparity between the two calibrations. The analyses of the field and glasshouse comparisons are still proceeding: an initial conclusion is that the Rothamsted and Crump porometers, when each calibrated with 'Celgard' film, did agree in their measurements on leaves of wheat, field beans and clover. (W. Day, Parkinson, Scott, Dunlop and Graham)

Photosynthesis

Photosynthesis: field studies. In preparation for a 1979 drought experiment, new equipment and procedures for measuring photosynthesis were evaluated during 6 weeks in June and July. Measurements were made on six small plots of spring barley, of which, after emergence, two were sheltered from rain, two exposed to rain, and two exposed to rain and irrigated. On these barley plots, stomatal resistances to water vapour transport

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were measured with the Rothamsted continuous flow porometer and also with a portable leaf chamber that can simultaneously measure photosynthesis and stomatal resistance (*Rothamsted Report for 1977*, Part 1, 202). The leaf chamber estimates were consistently higher, particularly for the droughted plots, and it was concluded that the leaf chamber caused a progressive stomatal closure over a period of 4–5 min. In studies that require absolute values for rates of photosynthesis it will thus be necessary to use both the porometer and the photosynthesis chamber so that the effects of this closure can be quantified. (Parkinson, W. Day, Leach and Joyce)

Five of these photosynthesis chambers, two for leaves and ears and three for stems and leaf sheaths, were deployed on the six barley plots. Procedures were evolved which allowed them to be collectively used to make measurements, on two plots simultaneously, of the rates of gross photosynthesis at six carbon dioxide concentrations and at six light intensities. The carbon dioxide was dispensed at the required concentrations by a portable gas mixing apparatus (*Rothamsted Report for 1977*, Part 1, 202), and the various light intensities were obtained by appropriate screenings of the solar irradiance and, in variable daylight conditions, by incandescent and fluorescent lamps (these lamps provided an uneven, low intensity irradiance; a more uniform and intense artificial field irradiance will be provided in 1979 by a 1000 W mercury vapour lamp). Each leaf chamber was operated as a continuous flow instrument, and its estimate for a rate of photosynthesis was derived from measurement by infra-red absorption of the concentration of carbon dioxide in the outflowing gas stream. A suitable technique was proved in which this outflow stream was made to flow through a vented 50 ml syringe for 2 min. After this interval, the syringe was sealed and, with minimum practicable delay, its contents were discharged through the 5 ml sample tube of an infra-red gas analyser; the analyser signal was recorded immediately the discharge was completed. Many data were collected during the 6 weeks of experimentation on the six barley plots, and these are being used to test mathematical models and develop computer programs that will support the analysis of the 1979 drought experiment. (Parkinson, W. Day, Croft, A. T. Day, French, Leach, Dunlop, Joyce, Scott and Strange)

Another chamber has been modified so that, with a leaf in the chamber, the inflow of air and carbon dioxide can be interrupted and a small volume of $^{14}CO_2$ injected. A sample of chamber air is withdrawn 10 s after the injection, and the leaf removed and preserved in liquid nitrogen. By analysing for radioactivity the air and leaf samples, the rate of photosynthesis can be determined, and can be related to the chamber measures of transpiration, irradiance and temperature at the time of injection. (Leach, with Lawlor, Botany Department)

Photosynthesis: laboratory studies. In constant environment chambers, experiments on wheat and barley plants have sought to measure the effects of temperature on the parameters a, b, of the photosynthesis model that will be used in the analysis of the 1979 drought experiment (*Rothamsted Report for 1977*, Part 1, 202). At 12·5, 20 and 27·5°C, with the water vapour pressure deficit fixed at 6·0 mb, leaf chamber measurements were made of the dependence of net photosynthesis of single leaves on carbon dioxide concentration and, separately, on light intensity. Nine concentrations of carbon dioxide and seven light intensities were used, respectively provided by the gas mixing apparatus and by wire mesh screening of the fluorescent irradiance. Analysis of the data is proceeding. (Leach)

Root observations. The ground area that is available, under the mobile shelter, for a drought experiment is too small (331 m^2) to allow sacrifice of soil in excavational sampling of root volumes and rooting depths. Techniques for non-destructive observation of root

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systems are therefore being sought so that estimates of the root mass, and its vertical distribution, can be furnished for the yield response model. Following the method of Waddington (*Canadian Journal of Botany* (1971), **49**, 1850–1852), ten perspex tubes and two glass tubes, 44 mm diameter and 1·5 m long, have been inserted to their full length at an angle of 45° to the vertical (i.e. to a soil depth of 1·0 m) under crops of winter wheat, field beans and spinach on a neighbouring field. As the crops grow, roots appear at the surface of the tubes, and they have been both observed and photographed above ground by means of an 'Introscope' light guide. (W. Day, A. T. Day and Croft, with Welbank, Botany Department)

Soil physics

Soil structure

Collaboration. The Department's contributions to the multi-disciplinary working group on soil structure were described in *Rothamsted Report for 1977*, Part 1, 194. These contributions, with those of the other collaborators, have been accepted for publication by the *Journal of Soil Science*, and will appear, in 1979, as a set of seven papers within a single *Journal* issue.

Gaseous diffusion in dry, natural and remoulded crumbs. In the working group's collaboration, diffusion coefficients were measured, for hydrogen gas, on 26 samples of crumbs prepared from various horizons of soils from six soil series. The results were discussed (*Rothamsted Report for 1977*, Part 1, 194–196) in terms of pore shape, but not pore size. For hydrogen at atmospheric temperatures and pressures, the mean free path of the hydrogen molecule is 110 nm, and, because of molecular collisions with the pore walls, the effectiveness for diffusion of unit pore volume (described by $D_c/D_o\epsilon_c$) decreases with decreasing pore size for pores comparable in width to this mean free path. For oven-dried crumbs from 15 of the 26 soil horizons, collaborative measurements have been made of the fractions of total pore volume that are contributed by pores of less than 110 nm width. These fractions ranged from 0·45 to 0·97, and a regression on them, for the 15 samples, of $D_c/D_o\epsilon_c$ gave a highly significant ($P < 0{\cdot}01$) negative correlation, confirming that pore width, as well as pore shape, does influence the effectiveness for diffusion of unit pore volume. (Currie, with Newman, Soils and Plant Nutrition Department)

Measurements of diffusion coefficient and of crumb porosity have been made, also, for natural and remoulded crumbs of Parklands soil. Natural crumb porosity, already large at 0·37, was increased by remoulding, to 0·44, in accord with previous experience. Diffusion in the reformed aggregates, however, was some 40% more rapid than would be expected from the increased porosity alone, indicating that the reformed aggregates have a less complex pore system than do the natural aggregates. For both sets of aggregates, several cycles of wetting and incubation were found to increase aggregate stability but to cause no significant changes in crumb porosity or pore complexity. (Currie, with Skinner, Soil Microbiology Department)

Gaseous diffusion in compacted soils. At field capacity, tilled soils may be easily compacted, with probable detriment to the diffusion through them of oxygen and carbon dioxide. In a laboratory experiment, measurements have been made of the effects on gaseous diffusion coefficients of the various degrees of compaction that were imposed at field capacity on a set of tilled soil crumbs. At field capacity, when the pores within the crumbs are saturated and those between the crumbs are drained, the effect of a sudden compression of a bed of crumbs is to subject each crumb to a plastic deformation, in which the shape, but not the volume, changes, and to decrease the total volume of the

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bed. This loss of total volume is almost entirely attributable to the loss of those inter-crumb pores that are essential if gases are to diffuse through the bed. Seven beds of crumbs, each at field capacity, were variously compressed to give airfilled porosities, ϵ_a, that ranged from 0·34, a most loose packing, to 0·04, a completely compacted state. Over this range, the diffusion coefficient, D, could be expressed:

$$D/D_o = \epsilon_a^{1 \cdot 7}$$

where D_o is the diffusion coefficient with no impeding solids. When extrapolated to the interval $0 < \epsilon_a < 0 \cdot 04$, in which there were no measurements, the observed data gave no indication that D would equal zero for any ϵ_a other than zero: i.e. there was no threshold porosity. If the porosity of the most loosely packed bed had been reduced by progressive wetting, instead of compaction, then, as the inter-crumb pores became filled, the diffusion would have decreased more powerfully: in proportion to the fourth power of the remaining airfilled pore space. Thus, in the short term, although compaction is detrimental to aeration, flooding is more so.

For these same beds of crumbs, measurements showed that the air porosities at field capacity were reduced by compaction, and that their new range was $0 \cdot 33 > \epsilon_a > 0 \cdot 01$. The water contents at field capacity were correspondingly increased. The interpretation of these changes is that as the crumbs were brought into closer proximity there was an increase in the volume of water held in the inter-crumb pendular rings. Measurements of diffusion on compacted beds that had been rewetted to field capacity conformed to the relationship $D/D_o = \epsilon_a^{1 \cdot 7}$, indicating that the pore space occupied by this additional pendular water played little part in conducting gases through the beds. (Currie)

Tillage. A 1977 tillage experiment (*Rothamsted Report for 1977*, Part 1, 196) sought to determine whether tillage treatments, and the soil water content in the 0–30 cm layer at the time of tillage, caused or promoted measurable changes in the physical properties of the soil and whether these changes could, in turn, be related to crop growth and yield. The analyses of the data from that experiment are well advanced, and the initial findings are presented in this and in later sections of this report. In preparation for a 1979/80 tillage experiment, the site was made more uniform by cultivating all plots to 40 cm depth in August 1978.

In the 1977 experiment, profiles with depth z of heat flux G and temperature T were measured on one cultivated and one uncultivated plot, both fallow. From the identity $G = \lambda\, dT/dz$, values were calculated for the corresponding profiles of thermal conductivity, λ. Values for the profiles of λ were also derived from measurements of the variations with depth of the amplitude and phase of the diurnal waves of soil temperature on the two plots. A third set of estimates for λ was obtained through a theoretical relationship of the conductivity of the bulk soil to that of its constituents—quartz, clay, water and air. Because the temperature wave estimates may more readily be derived when the amplitudes of successive waves are equal, the analyses were directed initially to the period 2–7 July 1977 that comprised a succession of cloudless days. For that period, the three methods gave profiles for mean daily λ, averaged over cultivated and uncultivated plots, that were equal within the limits of their large uncertainties. The uncertainties were least for the heat flux method, and representative values for λ by this method were 0·6 W m^{-1} K^{-1} and 1·8 W m^{-1} K^{-1} in the 0–2 and 15–30 cm layers, respectively; the corresponding temperature wave estimates were 0·9 and 1·4 W m^{-1} K^{-1}. Much of the λ-variation with depth could be attributed to differences in volumetric water content which, typically, was 0·1 near the surface and 0·3 at 30 cm. The differences in λ between cultivated and uncultivated plots were much less than those arising through the different methods of estimation, and it is concluded that, during 2–7 July 1977, no

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significant differences in thermal conductivity profiles could be ascribed to the effects of cultivation. However, the cultivations had been made in April 1977, and by July any differences in thermal parameters in the surface soils could have disappeared as the soils settled. Analysis is now therefore being directed to data gathered earlier in the season. (Brown, North, Dawes and Wilson)

Soil water

Soil water movement in heterogeneous soils. The physical laws that govern the movement of soil water and the development of water profiles are well established for uniform soils. However, real soils are often non-uniform, and the development of water profiles will be affected by any non-uniformity. Studies are therefore in progress to determine how water profiles develop in two-layered soils—such as might occur when a uniform plough layer overlies a uniform subsoil of different hydraulic properties. From such studies it is hoped to assess the relative importance to water movement of the various physical properties of the two layers.

Under controlled experimental conditions, the development of water profiles has been observed in columns filled, in two layers, by two materials with pores of different size but similar shape. Various initial and boundary conditions were imposed upon the columns, and their influences investigated, the hysteretic properties of the wetting and drying processes having previously been determined on the same columns. In a representation of this system that gives rise to equations that are more readily solvable, the depths of the layers and the times of duration of flow are scaled according to similarity principles so that the corresponding scaled hydraulic properties are identical in the two layers—and a source term can then be imagined to act at the layer boundary. It may be remarked that the same mathematics can be applied to the situation where water moving vertically through a soil is subject to abstraction, as by plant roots. The use of scaling techniques is being further exploited in these experiments by inclining the columns: their effective length is thereby increased (or, equivalently, the effect of gravity is reduced), and measurements can consequently be made with greater precision. (Youngs and Price)

Soil water movement in swelling soils. Real soils are heterogeneous; in addition, many are prone to swell as they wet. The basic laws of soil water movement, and most of the confirmatory experimental work, relate to non-swelling soils, and any swelling-soil generalisations of these laws must allow for two important and complicating factors. First, Darcy's Law that relates velocity of water flow to the gradient of hydraulic potential refers that velocity to the moving soil particles, rather than to a fixed coordinate. Second, the equilibrium water content in any elemental volume of soil depends not only on the pressure in the soil water, but also on any mechanical forces that may be exerted on the soil matrix, as by the weight, in the field, of the soil and soil water that overlie the volume. In preparation for experimental studies of the combined effects of water pressure and mechanical loading on the water content of clay soils, a triaxial shear test apparatus, on long term loan from the University of Bristol, is currently being tested and calibrated. In addition, a new design of hydraulic conductivity cell has been conceived, and a prototype apparatus is under construction. This cell will be used to examine the hydrodynamics of one-dimensional steady flow in constrained, saturated, swelling soils. A particular feature of the cell is its facility to permit separate segments of the clay column to be rapidly isolated and sealed in readiness for subsequent determinations of their water contents. (Towner)

Hydrodynamic dispersion. The dispersion of soil water solutes crossing an interface

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between two regions of uniform but different pore sizes has been simulated in a one-dimensional laboratory experiment. The interface, in a horizontal column, was between glass beads of two diameters through which water and the solute, a dye, could be caused to flow. From an analysis of the dye concentration profiles along the column it is possible to calculate the conditions of continuity for the flux and concentration at the interface. (Towner and McGeown)

Land drainage theory. Current work in drainage theory has been directed to the problems of soils that are heterogeneous of structure, and by implication, of hydraulic conductivity. For ditch draining of heterogeneous soils, designs may be formulated through Youngs' extension (Youngs, *Journal of Hydrology* (1965), **3**, 283–296) of Charnyi's seepage analysis of horizontal groundwater flow (Charnyi, *Doklady Akademii Nauk* (1951), **79**, 937–940). This extension has now been shown to be applicable also in other situations, as in designs for well drainage. For pipe drains, seepage analysis cannot be exploited because the boundary conditions are not completely defined; but hodograph analysis can be applied, predicting, for uniform soils, the height of the water table that would result from a given rainfall rate. Knowledge of this height allows calculation of potentials just below the water table where the flows may be considered vertical. This approach can be developed and applied to that particular heterogeneous soil that is uniform horizontally but in which hydraulic conductivity varies with depth. Here, the condition of vertical flow, and the variations in hydraulic conductivity, lead to changes with depth in the hydraulic resistances to water flow. From these changes it is possible to determine, for such pipe-drained land, the water table height as a function of rainfall rate. (Youngs)

Hydraulic conductivity measurements. In any applications of theory to the design of drainage schemes for heterogeneous soils, it is necessary to know the variation with depth of hydraulic conductivity. In a uniform soil, the hydraulic conductivity can be determined from the rate of inflow of water to an augered hole, and this method is being modified to make it suitable for layered soils. To furnish the supporting theory, a new exact method has been developed to calculate the initial rate of flow to a ditch from a level water table when the ditch water level is suddenly lowered; and this method has been adapted for analysis of radial flow to an augered hole. This theory must now be extended to allow for variations of hydraulic conductivity, and work is in progress to that end. (Youngs)

The variation with depth of hydraulic conductivity was studied also in the 1977 tillage experiment, where an existing method, the instantaneous profile method (Hillel *et al.*, *Soil Science* (1972), **114**, 395–400) was used to measure the hydraulic conductivity at 10, 25, 35 and 50 cm depth on a cultivated and on an uncultivated plot. At these depths, and for two replicate sites per plot, simultaneous *in situ* measurements were made of soil water content, by the neutron scattering method, and of soil water pressure, by tensiometers, during the period of vertical redistribution of water that followed a deliberate flooding of the plots. Evaporation from the plots was prevented by plastic covers. The results showed that, for volumetric water contents below 0·3, drainage fluxes were higher on the cultivated plot: at a water content of 0·2, flux densities on the cultivated and uncultivated plots were respectively 0·2 and 0·02 mm d^{-1}; at water contents above 0·3, flux densities were similar, $\sim$1 mm d^{-1}, on both plots. Measured values for soil water pressure were highly variable, and the hydraulic conductivities derived from them had insufficient precision to reveal differences between plots or variations with depth. Ways of improving the measuring technique will be sought for incorporation into future tillage experiments. The average, over plots and depths, of hydraulic conductivity showed an approximately

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exponential relation to soil water content, and ranged from 3 mm d^{-1} at 0·4 to 0·15 mm d^{-1} at 0·25 volumetric water content. (North and Wilson)

Water content and water potential relationships. The derivation of field relationships between soil water content and soil water potential for soil at various depths on five of the drought experiment plots was described in *Rothamsted Report for 1977*, Part 1, 200. These water characteristics differed from those measured in the laboratory on repacked crumbs that had been sieved from the same sites. For soils from the adjacent tillage experiment site, corresponding characteristics are being measured for samples taken from 5, 10, 25 and 35 cm depth under the compacted and under the fully cultivated plots. The measurements are being made on repacked crumbs and also on larger samples carefully withdrawn without disturbance. Because tillage is likely to affect only the macroporosity of the soil, differences in water characteristics that derive from different cultivations, or from the different methods of sample preparation, are being sought only in the water potential range −0·025 to −0·10 bar. Measurements have been completed for the compacted treatments only. Preliminary results show that the measured water characteristics for repacked crumbs and for undisturbed samples differed most for 35 cm depth—a depth that is just below the depth of cultivation and at which there is an increase in soil clay content. At the highest (least negative) potentials, the repacked crumbs held 8% more water per unit dry mass than did the undisturbed samples. Over the measured range of potentials, the water contents of the undisturbed samples were almost constant; furthermore, those for the three shallower depths were almost equal. Results for the repacked crumbs showed more variation, reflecting, in part, the variability of the packing process. (Brown, Dawes and Mal-Allah)

Water content measurement. At soil depths less than 0·25 m, measurements by neutron moderation of soil water content are subject to systematic error because of the depth-dependent loss of neutrons to the atmosphere. An empirical correction for this effect, based on neutron moderation measurements at various depths below a water surface, was derived by French, Long and Penman (*Rothamsted Report for 1972*, Part 2, 5–85). When applied to measurements in the 1977 tillage experiment, this correction gave rise to water content profiles that showed a seemingly spurious minimum at 5 cm depth. The validity of the correction procedure has therefore been tested, on the tillage plots, by comparing for various soil depths the neutron moderation values for soil water content that were obtained when the soil was, or was not, overlain by a tray of soil. This tray, 50 cm diameter by 25 cm high, fitted with a perforated aluminium base and filled with surface soil, effectively extended upward the height of the soil column. The comparison gave values for correction factors that depended on both soil depth and water content. Averaged over the measured range of water contents, these soil-derived corrections differed significantly from the water-derived ones of French *et al.* When applied to the moisture measurements of the 1977 tillage experiment, the new correction factors were usually, but not always, able to remove the spurious minima previously mentioned. Further investigations will be undertaken before the new correction procedures are fully adopted for routine processing of soil moisture measurements. (North and Wilson)

Staff and Visiting Workers

H. A. McCartney, formerly at the University of Lancaster, joined the Department in October to work on the movement of cereal disease spores. A. Poulovassilis extended for a second year his temporary appointment as Professor of Agricultural Hydraulics in the University of Athens; for the duration of this extension, R. I. Price will remain

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attached to the Department to pursue research in soil water physics. C. J. Gordon left in March to join Messrs Unilever, and M. Stead in September to resume full-time education. S. A. Strange, N. J. Fletcher and Mrs. A. E. Roberts joined the Department and respectively give assistance to aerobiology and soils research and to the Department's administration. Miss N. M. Mal-Allah, Institute of Agricultural Technology, Aski-Kelak, Iraq, completed her attachment to the Department; M. W. Dunlop, J. Joyce and A. J. McGeown all spent several months in the Department as sandwich course students, and R. Graham a few weeks as a vacation worker.

B. J. Legg attended the First International Conference on Aerobiology and the Third International Congress of Plant Pathology, both held in Munich, and T. Woodhead the Eleventh Congress of the International Society for Soil Science, in Edmonton, Alberta. E. G. Youngs presented a paper at the Fifth Meeting of the European Geophysical Society, in Strasbourg, and he and G. D. Towner gave a course of lectures on groundwater physics to M.Sc. students at the National College of Agricultural Engineering. T. Woodhead gave lectures in the Universities of Saskatchewan and British Columbia, and several members of the department gave lectures and presented papers at British Universities and conferences. E. G. Youngs, with staff of the Field Drainage Experimental Unit (Ministry of Agriculture, Fisheries and Food), prepared an exhibit of field drainage research for a Royal Meteorological Society Exhibition in July.

Publications

Book

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General Paper

2 Legg, B. J. & Bainbridge, A. (1978) Air movement within a crop: spore dispersal and deposition. In: *Plant disease epidemiology*, Ed. P. R. Scott & A. Bainbridge, Oxford: Blackwell Scientific Publications, pp. 103–110.

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4 (Bailey, R. A.), Preece, D. A. & Zemroch, P. J. (1978) Totally symmetric Latin squares and cubes. *Utilitas Mathematica* **14,** 161–170.

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12 MCCARTNEY, H. A. (1978) Spectral distribution of solar radiation II. Global and diffuse. *Quarterly Journal of the Royal Meteorological Society* **104,** 911–926.

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