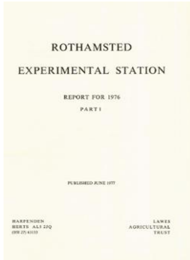
Report for 1976 - Part 1


ROTHAMSTED
EXPERIMENTAL STATION
REPORT FOR 1976
PART 1

Full Table of Content

Physics Department

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Introduction

During 1976 work in the Physics Department continued in three areas: soil physics, micrometeorology and plant physics. There was an increasing commitment to collaborative projects, both within the department and in association with other departments, a process encouraged by the intensive use of the mobile rain shelter at Little Knott that was described in detail in *Rothamsted Report for 1974*, Part 1, 202. The shelter was used in 1975 for an experiment on tillage (*Rothamsted Report for 1975*, Part 1, 230) and in 1976 for a plant physics experiment on the physiological response of spring barley to impositions of water stress of various severities at different growth stages. In anticipation of further intensive use of the mobile shelter site in future years, the laboratory accommodation at Little Knott was considerably expanded in 1976, the experimental plots and their surrounds were protected by flood-diverting drains, and improvements were made to the shelter drive mechanisms and controls.

Much of the work on soil physics was concerned with the collaborative programme of the Rothamsted Soil Structure Working Group, whose findings will be presented in a seminar presentation in mid-1977. Work continued on laboratory and field respiration, and measurements of soil carbon dioxide effluxion were made in support of the Little Knott drought experiment.

Very comprehensive sets of micrometeorological measurements were collected over irrigated and unirrigated spring barley on Great Field: these micrometeorological data permit the determination of the fluxes of energy and gases between the crop and its environment. On the same plots, collaborative measurements of soil water content, by the neutron scattering meter, and of transpiration and carbon dioxide assimilation, using a canopy enclosure (*Rothamsted Report for 1975*, Part 1, 236) afford independent measures of some of these fluxes. The experiments at Little Knott similarly profited from measurements of photosynthesis, using a new portable leaf chamber, and from neutron monitoring of the soil moisture content.

The experiment at Little Knott was planned and executed in partnership with members of the Botany Department, and members of the Physics Department have continued co-operative work with the Nematology Department and the Field Experiments Section. Planning has commenced for work that will be undertaken with the Plant Pathology De-

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partment on the aerobiology of spore dispersal, and the recruitment of a statistician/programmer to a joint post in the Statistics and Physics Departments has allowed a recommencement of the analysis of the backlog of micrometeorological records.

A welcome feature of the last quarter of 1976 has been the commencement of analysis and writing-up of several projects that have simultaneously come to fruition.

Plant physics

Plant response to water stress

Yield response: Little Knott. Drought has depressed barley yields frequently at Woburn and occasionally at Rothamsted, and water deficits in spring may depress yields more than deficits later in the season. The effects on yield of droughts of various intensities at different growth stages were investigated at Little Knott in 1976 by imposing such droughts, as 12 treatments, on 24 small plots (4·6 × 3·0 m) of spring barley. The mobile shelter excluded precipitation from all plots, and the water deficits were controlled by the supply and withholding of trickle irrigation. Yield and yield components were measured for each plot, but plant responses were also evaluated in terms of water use, photosynthetic rate, and physiological and morphological development, with many collaborators contributing their particular expertise, and with five of the 12 treatments being replicated three times and designated for intensive measurement and analysis.

The 12 treatments differed only in their watering; each had a single drought period, of which the duration and date of commencement were the only imposed variables. Irrigation water was applied weekly in amounts equal to the preceding week's transpiration, as measured by neutron scattering monitoring of soil water depletion in the most-watered plots. The crop was sown on 31 March, and all plots were maintained at field capacity until emergence about 14 April; from 28 April, the wettest plots were watered weekly through the growing season, and the driest not at all. By 10 May, after two irrigations, there were clear differences in growth between irrigated and unirrigated plots, and by early June there were notable differences in stem extension. On all plots, ears emerged about 14 June, and anthers a week later. Ripening commenced in early July, plants on the driest treatment ripening three weeks ahead of those on the wettest.

Tables 1 and 2 show the harvest yields of grain, and 1000 grain weight for two groups

TABLE 1

Harvest data for spring barley on small plots at Little Knott, 1976

Dry matter yield for plots with maximum soil water deficit at harvest

Treatment number	3	7	9	10	11	12
Weeks of watering (consecutive from 28 April)	–	3	5	9	11	12
Grain yield (t ha^{-1})	2·75	3·35	3·55	4·55	5·60	
Standard error (t ha^{-1})	0·14	0·14	0·19	0·19	0·14	
1000 grain weight (g)	30·5	30·5	29·0	32·5	36·5	
Standard error (g)	0·7	0·7	1·0	1·0	0·7	

TABLE 2

Harvest data for spring barley on small plots at Little Knott, 1976

Dry matter yield for plots watered for three weeks, kept dry for various durations, and then watered until ripening

Treatment number	7	6	5	4	11	12
Weeks without watering	8	6	4	2	0	
Grain yield (t ha^{-1})	3·35	3·95	4·75	5·70	5·60	
Standard error (t ha^{-1})	0·14	0·14	0·14	0·19	0·14	
1000 grain weight (g)	30·5	34·5	39·0	40·0	36·5	
Standard error (g)	0·7	0·7	0·7	1·0	0·7	

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of treatments. Table 1 relates to plots that were irrigated for the stated number of weeks and then kept dry until harvest. Table 2 relates to plots each irrigated for three weeks, then kept dry for the indicated number of weeks, and then irrigated until ripening. (Data for treatments 11 and 12 have been combined, because their crops were nearly ripe before the treatments differed.)

For both groups, grain yields correlate inversely with length of dry spell; grain yield for the wettest treatments, 11 and 12, is double that for the driest (treatment 3). The 1000 grain weight is less variable, ranging from 29 to 40 g, but appears to be increased by the availability of water during the grain filling period. (W. Day, Legg, A. T. Day, French, Pritchard, Parkinson, Croft, Derry, Sayers, Scott, Dominy and Jeffers, with Lawlor and Sheila Davies, Botany Department)

Edge effects. The Little Knott plots were all small, 20 rows 4·6 m long, and some of the crop was therefore harvested in 15 and 25 cm samples along plant rows to reveal the existence of any plot edge effects. The results indicate that, for watering treatments, provided the peripheral 0·45 m of the plot is discarded, the harvest data give reliable, comparative yield measures. (W. Day)

In the soil, edge effects may be ascribed to the lateral growth of roots from one plot to another or to the horizontal movement of water across plot boundaries. Tritiated water, applied with the irrigation water, was used on two of the Little Knott plots on 26 May and 30 June to attempt to detect such lateral movement between well-watered and unwatered plots. The measurements of 26 May indicated that penetration of tritiated water from the wet to the dry plot was insignificant for horizontal distances exceeding 0·5 m. A more severe test, in cracked soil on 30 June, did indicate that small quantities of tritiated water were detectable 0·5 m within the dry plot. Analyses to assess the volume flow of water across the plot boundary are proceeding. (Legg and French)

Water use: weekly periods: spring barley: Little Knott. Access tubes for the neutron scattering moisture monitor were installed in 17 plots: one each in two of the three replicate plots of the five treatments selected for intensive study, and in one plot per treatment for the remainder. Measurements were made at the beginning of each week, at 19 depths in the top 1·5 m of soil, and the resulting moisture content values, and the week's total of crop water use, were available to guide the Wednesday irrigation programme. Early in the season, the standard deviation of water use estimates for replicate plots was less than 3 mm; during the growing season the soils responded to the crop, the weather and the treatment, and the standard deviation increased to 10 mm, in comparison with an instrumental uncertainty of $\pm 1{\cdot}5$ mm.

For most of the season, the fully irrigated barley transpired at a rate of 1·2 E_T, in agreement with the 1·15 E_T reported by French, Long and Penman (*Rothamsted Report for 1972*, Part 2, 24), where E_T represents a modified form of Penman's estimate of potential transpiration (Penman, H. L., *Proceedings of the Royal Society*, Series A, (1948) **193,** 120–145). During the exceptionally hot and dry period from 22 June to 12 July transpiration proceeded at a rate of 1·4 E_T, probably as a result of advection of sensible heat from adjacent non-irrigated plots, but possibly representing a response of large areas of crop to these exceptional conditions.

Over the whole season, fully irrigated plants (treatments 11 and 12) transpired 400 mm of water: the non-irrigated (treatment 3) transpired 145 mm; other treatments were intermediate. When irrigation was terminated, transpiration continued at about 1·2 E_T until the soil moisture deficit reached 80 or 100 mm, when transpiration suddenly declined to 0·5 E_T or less. This decline occurred at the same deficit for a drought occurring at any time during the growing season. Plants on treatment 3 matured earlier than the others,

https://doi.org/10.23637/ERADOC-1-133

when their soil moisture deficit was 135 mm. Treatment 7 attained the greatest soil moisture deficit, 174 mm, and yielded about 20% more grain than treatment 3. Total water use correlated well with grain yield and with total dry matter, but there is evidence that water use is reduced proportionately more by water stress than is dry matter production.

During periods when irrigation was withheld, the plants abstracted water from progressively greater depths as the roots extended down the profile. Plants to which water had been well supplied early in the season responded, on the withholding of water, by abstracting water within one week from depths as great as 1·2 m. (French, Legg, Croft, Gordon and Jeffers)

Water use: hourly periods: spring barley: Little Knott. The neutron scattering technique does not afford estimates of transpiration for periods of less than one week. An understanding of the dynamics of plant response to water stress requires *hourly* measurements of transpiration, stomatal resistance, and soil and plant water potential.

Monteith (*Symposium of the Society for Experimental Biology* (1965), **29,** 205–234) has developed a mathematical model that describes hourly transpiration in terms of air temperature and humidity above the crop, leaf area index, stomatal resistance to water vapour flow, wind speed and net radiation intercepted by the crop. One replicate plot from each of the five intensive-study treatments was instrumented to record the meteorological variables; stomatal resistance was measured by a continuous flow porometer developed for this experiment, and leaf area index was monitored by destructive sampling supported by preliminary trials with a fish-eye lens and camera. Data were logged throughout the season, and analysis is proceeding. For a typical day, summation of the hourly values of transpiration from Monteith's model gave daily totals of 5·4 and 3·0 mm for fully irrigated and non-irrigated plots respectively; the neutron scattering method gave estimates of 30 and 18 mm for the corresponding weekly water use. (W. Day, Legg, Jeffers and Newell)

A more detailed understanding of plant water use requires, in addition to those variables incorporated in Monteith's model, measurements of leaf and soil water potential. Leaf water potential was measured four or five times per day on the intensive treatment plots using a pressure chamber, and the osmotic component of leaf water potential and the leaf relative water content were measured on detached leaves. Soil water potentials were measured on the same five plots, using tensiometers of range 0 to −0·8 bar at depths of 15, 30 and 60 cm, and soil psychrometers of range 0 to −30 bar and sensitivity 0·3 μV bar^{-1} at depths of 10, 20, 40, 60 and 100 cm. The soil psychrometers are still undergoing trial; there are problems with installation: the sensors need to lie horizontally, and contamination of the thermojunctions leads to loss of sensitivity. (W. Day, Derry and Sayers, with Lawlor, Botany Department)

Water use: monthly periods: turf. The soil moisture content under the turf of the meteorological enclosure at Rothamsted was monitored weekly, by neutron scattering at two replicate sites, from the beginning of March when the soil was close to field capacity. These measurements, in monthly summary and with the corresponding rainfall totals, are displayed and used in Table 3 to calculate the actual transpiration and its relation to the modified Penman (1948) estimate of potential transpiration, assuming 25% reflection of shortwave radiation. For this soil, the ratio, E_A/E_T, of actual to potential transpiration decreases linearly with actual soil moisture deficit, Δ; the correlation is highly significant:

$$E_A/E_T = 1{\cdot}04 - 0{\cdot}0041\ (\Delta/\text{mm}) \quad (r^2 = 0{\cdot}99,\ n = 6).$$

The difference, for turf, between the seasonal totals of actual and potential transpiration was 235 mm. Deeper-rooted vegetation would show a smaller difference, but fallow

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TABLE 3

Calculation of transpiration from turf, Rothamsted, 1976

(All values, except the ratios, in mm)

Month	Rainfall (1)	Measured cumulative soil moisture deficit (2)	Monthly increment of soil moisture deficit (3)	Calculated actual transpiration (1) + (3)	Potential transpiration (after Penman)	Ratio of actual to potential transpiration
March	18	18	18	36	37	0·97
April	22	48	30	52	61	0·85
May	22	87	39	61	92	0·66
June	17	130	43	60	119	0·50
July	42	145	15	57	124	0·46
August	9	171	26	35	103	0·34
Totals	130	171	171	301	536	

and impermeable ground a larger one. An order-of-magnitude difference for south-east England might therefore be 200 mm. The solar energy that would have evaporated this 200 mm of water was dissipated, in major part, in sensible heating of the soil and atmosphere during June, July and August, helping to maintain the exceptionally high temperatures and transpirational demands during these months. (French)

Water use: laboratory studies. The stomatal resistance to water vapour flow may be calculated from the width, length and area density of stomatal apertures. A leaf chamber has been built that fits onto a microscope stage, the microscope being fitted with a camera and a ×400 long-working-distance objective so that stomata can be photographed and their dimensions and resistances calculated through various published formulae. The microscope lamp illuminates the leaf both to permit photography and to maintain photosynthesis.

Transpiration of the leaf into the chamber affords an independent measure of this stomatal resistance. As water vapour is transpired by the leaf into the chamber, it is mixed, by a small fan, with dry air that is fed into the chamber at a known rate. The mixed gas is passed to a dew point meter that measures its humidity. The temperature of the leaf in the chamber may be controlled by a Peltier cooling block and measured by a thermocouple. Knowing the humidity of the mixed gas, the leaf temperature, the gas flow rate and the leaf area, a value for the stomatal resistance may be derived that can be compared with that obtained by photography.

At a given instant, the stomata on any one leaf exhibit a range of apertures; indeed, there is difficulty in defining what constitutes the stomatal aperture. Experimentally, there is measurement uncertainty in the leaf and dew point temperatures. Nonetheless, preliminary data indicate good agreement between the stomatal resistances derived from dimensions and from transpiration, and additional measurements are proceeding. (Parkinson and Dominy)

Photosynthesis: field studies. A portable leaf chamber has been developed that allows field measurements of photosynthesis over periods as short as one minute. A growing leaf is sealed by an inflatable rubber diaphragm into the inner of two concentric, transparent acrylic tubes. The outer tube, by absorbing infra-red light, and the air that is blown between the two tubes, cool the inner tube, of 100 ml volume, that comprises the leaf chamber; air in the chamber is stirred by a small fan to promote convective cooling of the leaf whose temperature, under field conditions, does not exceed ambient by more than 2 K. Air temperature and light intensity are measured within the chamber.

By a novel technique, dry air of constant carbon dioxide concentration is fed at a pre-

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cisely controlled rate into the leaf chamber. Following insertion of the leaf and a one minute delay for equilibration, a 5 ml sample of the chamber exhaust gas is withdrawn by syringe for determination of its carbon dioxide concentration by an infra-red gas analyser. Knowing the leaf area, the gas flow rate, and the difference between input and output concentrations of carbon dioxide, the rate of photosynthesis can be calculated.

Extensive measurements on spring barley at Little Knott in 1976 await analysis; there is evidence that photosynthesis is reduced markedly when air temperatures exceed 30°C. (Parkinson and Dominy)

In 1974 and 1975 a field canopy enclosure was used to compare the photosynthetic rates of irrigated and unirrigated potatoes and wheat. (*Rothamsted Report for 1975*, Part 1, 236). Analysis of these experiments has been completed: the data lend support to Monteith's model of photosynthesis (Monteith, *Annals of Botany* (1965), **29,** 17–37). From that model, the combined stomatal and mesophyll resistances to carbon dioxide transfer were calculated, and were found to increase with crop age. However, measurements showed that the stomatal resistances remained constant, and it is concluded that, for wheat and potatoes, mesophyll resistances increase with age.

Between April and July 1976, over irrigated spring barley on Great Field I, the same enclosure was used on 24 separate days to collect additional data, on carbon dioxide uptake, transpiration, aerodynamic and stomatal resistance to water vapour flow, light intensity, and leaf, air and soil temperatures, that would be suitable for insertion in and evaluation of various crop growth models. Between 10.00 and 13.00 h GMT on those of these days that were almost cloudless, the 0·4–3·0 μm solar irradiance within the enclosure ranged gradually from 400 to 450 W m^{-2}: photosynthesis was light-saturated at 400 W m^{-2}. During these light-saturated periods, the temperature, humidity and carbon dioxide concentration of the enclosure air were subjected to controlled variations. At fixed humidities and carbon dioxide concentrations, barley's photosynthetic response to temperature was investigated, in 5 K increments, over the range 10 to 30°C: photosynthesis was maximal at 24°C, and half-maximal at 15 and 30°C, the high-temperature decline in photosynthesis probably being caused by stomatal closure. It is emphasised that this response, like those found previously for potatoes and wheat, relates to field-grown plants; similar findings have been reported for laboratory and glasshouse plants.

For spring barley, measurements of photosynthesis made with controlled, reduced concentrations of carbon dioxide in the enclosure, suggested that the compensation concentration of carbon dioxide, at which photosynthetic gain and respiratory loss of carbon dioxide are in balance, is about 150 vpm. The enclosure has also permitted measurements of dark respiration and soil and root respiration. (Leach)

Photosynthesis: laboratory studies. Between germination and that stage of growth at which leaf area index equals unity, a crop fails to intercept a portion of the available irradiance: leaf extension and the development of leaf area are therefore important processes during this period. Furthermore, there is evidence for some species that early growth may be restricted if day and night temperatures differ greatly: high day temperature leads to high photosynthate production, this synthate will not be used if the ensuing night is cold, and there will be a consequent accumulation of photosynthate that will inhibit further photosynthesis.

Pots of field beans were grown in two controlled temperature environments: one environment was maintained at 18°C day and night, the second at 18°C during the day and 5°C at night. Compared to the plants experiencing warm nights, plants subjected to cold nights had shorter stems, fewer leaves and reduced leaf extension rate, their daytime photosynthetic rate per unit leaf area was halved, and their resistance to carbon dioxide transfer was 30% higher. Plants from the cold night environment, when transferred to

https://doi.org/10.23637/ERADOC-1-133

that with warm nights, equalled, after only two warm nights, the continuously-warm plants in both rate of photosynthesis and in resistance to carbon dioxide uptake. (Leach)

Agricultural meteorology

Equipment, crops and processing. In 1976, the macro-plots on Great Field I were planted with spring barley, as were the small plots under the mobile shelter on Little Knott: the experiments were thus mutually supporting. Of the macro-plots, one was irrigated, the other not. Both plots were fully instrumented to measure micrometeorological variables above and within the canopy and in the soil, and the data were recorded on paper tape. Frequently-changing variables were recorded at 6-min intervals, other variables were logged as hourly means, and the most important data were both logged and displayed continuously on chart recorders. Data losses were insignificant. (Long)

Including these 1976 data, there are now high quality data in computer-compatible form for kale, beans, potatoes, spring wheat and spring barley; analysis of all these data re-commenced in October 1976 when a statistician/programmer joined the department. (Legg, Long and Zemroch)

Irrigation and crop growth: Rothamsted

Spring barley. The macro-plot barley was sown on 5 March, germinated by 25 March and showed visible response to irrigation by 25 May. Seasonal growth, as measured by plant extension, continued until 16 June, and the non-irrigated crop matured about six days before the irrigated. Ears were fully grown by 20 June, and a few light showers and some heavy dews caused the ears, but not the stems, to bend in the direction of airflow, effectively altering both the crop height and the airflow pattern within the crop. A similar phenomenon was observed for wheat in 1957 (Penman & Long, *Quarterly Journal of the Royal Meteorological Society* (1960), **86**, 16–50).

The micrometeorological data will be analysed rigorously to quantify the influence of irrigation on water use, plant response, and particularly on those aspects of airflow and turbulent diffusion that can only be investigated on macro-plots. For the exceptional summer of 1976, during which the non-irrigated plot developed a potential soil moisture deficit of 270 mm by 25 July, some influences were easily discerned. The temperature and humidity profiles, the leaf temperatures and the quantities and persistence of dew differed greatly between the two plots. The soil heat fluxes below the two plots were similar, but the very different heat capacities gave rise to large differences between soil temperature profiles.

Before harvest, the numbers of barley ears per metre row were sampled for each plot, and the results are presented with the yield data in Table 4. Irrigation increases yields of both grain and straw, but the straw response is perhaps greater. The ratio of grain yields is close to the ratio of ears per metre row on the respective plots: it may be, therefore, that the plants responded to irrigation through a greater survival of tillers. (Long)

TABLE 4

Harvest data for spring barley on the Great Field macro-plots, 1976

	Non-irrigated	Irrigated	Irrigated/non-irrigated
Grain (t ha^{-1})	$4 \cdot 12 \pm 0 \cdot 21$*	$5 \cdot 05 \pm 0 \cdot 25$	$1 \cdot 23 \pm 0 \cdot 09$
Straw (t ha^{-1})	$2 \cdot 54 \pm 0 \cdot 13$	$3 \cdot 47 \pm 0 \cdot 17$	$1 \cdot 37 \pm 0 \cdot 10$
Grain/straw	$1 \cdot 64 \pm 0 \cdot 12$	$1 \cdot 45 \pm 0 \cdot 10$	$0 \cdot 88 \pm 0 \cdot 09$
Ears per metre row	$115 \pm 1 \cdot 5$	$133 \pm 1 \cdot 7$	$1 \cdot 16 \pm 0 \cdot 02$

* Measured yields have been assumed uncertain to $\pm 5\%$, in accord with previous experience.

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Great Field plots adjacent to the macro-plots were used to investigate the response of spring barley to irrigation combined with nitrogen and fungicidal treatments. For nitrogen, a comparison was made between 50 kg ha^{-1} applied either entirely to the seed bed or in equal portions to the seed bed and as top dressing. For fungicides, plots treated with ethirimol seed dressing plus tridemorph foliar spray were assessed against untreated controls. The four irrigation regimes were: (i) none, (ii) 80 mm applied in three waterings in early June, (iii) 80 mm applied in three waterings in early July, and (iv) 125 mm applied in five waterings during June and early July. For these four regimes, the grain yields at 85% dry matter were respectively 4·45, 5·25, 5·07 and 5·38 t ha^{-1}. Nitrogen responses are not yet available, but the fungicides increased mean grain yield from 4·7 to 5·4 t ha^{-1}. (French, Legg, Croft and Gordon, with Jenkyn, Plant Pathology Department)

Maize. On Great Field II, an experiment was conducted to evaluate the response of forage maize to 180 mm irrigation, applied in seven waterings between mid-June and late August and in combination with the four nitrogen treatments, in kg ha^{-1}: 50, 100, 150, 100 + 50 top dressing. The yields, of total above ground dry matter, are summarised in Table 5. There are clear responses to irrigation and to nitrogen, and a non-significant suggestion that lack of rainfall prevented the use of the top dressing on the unirrigated plots. (French, Legg, Croft and Gordon)

TABLE 5

Effects of irrigation and nitrogen on the yield of forage maize, 1976

Yields in t ha^{-1} of total above ground plant matter at 85% dry matter

Nitrogen (kg ha^{-1})	50	100	150	100 + 50 top dressing	Means (SED 0·9)
No irrigation	9·4	10·0	10·3	9·6	9·9
Full irrigation	11·8	13·1	13·3	13·4	13·0
Means (SED 0·6)	10·6	11·5	11·8	11·5	

SED within table: horizontal comparisons: 0.8 t ha^{-1}
vertical comparisons: 1.1 t ha^{-1}

Spring beans. Yields of spring beans at Rothamsted vary considerably from year to year; on the Great Field irrigation experiments, yields have ranged between 1·4 and 4·8 t ha^{-1}. Various factors affect yield, and the Physics Department contributed irrigation expertise to a multi-disciplinary experiment that studied also the effects of nitrogen, nematicide, soil and foliar insecticide, soil fungicide and foliar aphicide. A full report appears on p. 150, but waterings of 39 mm in May, 100 mm in June and 126 mm in July produced taller plants that were harvested three weeks later than the unirrigated. In the dry conditions of 1976, the irrigation yield response, from 1·65 to 3·05 t ha^{-1} at 85% dry matter, exceeded that of any other treatment. The ratio of these yields, 1·8, is similar to that obtained in 1970. However, the maximum potential soil moisture deficit in 1976 was 290 mm, compared with 160 mm in 1970. The fact that irrigation did not give greater proportionate yields in 1976 than in 1970 suggests that in 1976 even the irrigated plants were stressed by the exceptionally high temperatures and transpiration rates. (Legg and French, with McEwen, Field Experiments Section, and others)

Farm crops. A full analysis of 12 years' irrigation experiments at Rothamsted is in progress, and when completed will complement the similar analysis for Woburn (*Rothamsted Report for 1972*, Part 2, 5). (Legg and French)

Irrigation and crop growth: Woburn

Potatoes (Nematology experiments). The 1976 experiment involved irrigation, two varieties of potato, two plant spacings, and a nematicide treatment. The irrigated plots

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received 100 mm in each of June, July and August, and 25 mm in September. (Legg—as adviser)

Analysis has been completed on soil moisture concentrations monitored by neutron scattering on Butt Close in 1971. These data have been correlated with distributions of potato roots infested with potato cyst-nematodes. (Brown, with Evans and Trudgill, Nematology Department)

Soil physics

Soil structure

Collaboration. In an inter-departmental working group, established to co-ordinate the various Rothamsted researches into soil structure, individual members are assessing, by their own specialist techniques, samples of soils carefully selected as paired comparisons. The department has lent strong support to the group in studies of crumb porosity, gaseous diffusion within crumbs, and dispersion stability.

Crumb porosity. In most soils the pore system is heterogeneous; large, more continuous pores ramify freely through the bulk soil to depth, dividing it into discrete zones, the crumbs, that have much smaller pores, usually in a more compact fabric. In field soils, the inter-crumb pores generally contain less water and more air per unit of their volume than do intra-crumb pores: the former allow roots to move freely through the soil bulk; the latter, although less accessible to roots, satisfy the plants' needs of water and nutrients, but are more likely to become anaerobic; they contribute less, per unit of air-filled volume, to gaseous diffusion.

In each of the three paired series so far sampled, crumb porosity at most depths, but excluding the surface layer, is significantly greater in the commonly problematical soil (Table 6). It is possible that because of these greater capacities for water, the latter soils may be more prone to plasticity when worked, and hence more difficult to manage. An increase of porosity with depth, as manifest by the Denchworth, Evesham, Ragdale and Hanslope samples, is characteristic of arable soils; a decrease, as for the Salop and Flint samples, occurs in soils under long leys. The porosity values of Table 6, if converted to corresponding crumb bulk densities, range from 1·7 to 2·1. A density of 2·1 for the bulk soil would, agriculturally, be totally unacceptable: it may therefore be that some crumbs cannot be usefully explored by plant roots. (Currie & Scott)

TABLE 6

Range, from top to bottom of the profile, of crumb porosities in 1–2 mm sieved fractions of contrasted soil pairs

Commonly problematical series		Rarely problematical series	
Series	Range of porosity	Series	Range of porosity
Denchworth	0·19–0·26	Evesham	0·19–0·24
Ragdale	0·24–0·27	Hanslope	0·19–0·23
Salop	0·33–0·28	Flint	0·29–0·22

Crumb diffusion. The coefficient, D, of gaseous diffusion through granular materials loosely packed to porosity ϵ may be expressed:

$$D = D_o \epsilon^m$$

where D_o is the diffusion coefficient with no impeding solids and m, by theory, is a parameter representing granule shape: 1·5 for a sphere, and $>1{\cdot}5$ for all other shapes approximating either prolate or oblate spheroids. Over a range of ϵ, m remains constant for a particular material, and by experiment, is a valid parameter for materials not composed

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of discrete particles: it may therefore be considered a 'pore complexity factor'. An analogous parameter, m_c, may be defined for diffusion within an individual crumb:

$$D_c = D_o \epsilon^{m_c}.$$

Although individual crumbs are too small to permit direct measurement of D_c, it may be derived, with unavoidable 10% uncertainty, as the small difference between two larger determinations, D_T and D_V, of the diffusion coefficients for a packing of crumbs respectively at oven dryness, D_T, and with the small pores only blocked by an inert liquid, D_V.

An existing apparatus is being extensively improved and modernised to permit measurement of D_T and D_V using hydrogen gas. A satisfactory calibration procedure has been evolved, and some sources of systematic error recognised and eliminated. Further development is in progress to minimise the effects of convection, whereafter the apparatus will be employed in the comparison of the paired soil samples. (Currie)

Dispersion stability. The stabilities of the soils listed in Table 6 have been measured by ultrasonic dispersion (North, *Journal of Soil Science* (1976), **27**, 451–459). For each pair, perhaps surprisingly, the stability as measured by ultrasonic dispersion appeared to be the reverse of management experience. For the Hanslope site, the reversal might be attributed to the cropping history prior to sampling; in the next section of this report there is evidence that the organic carbon content exerts a strong influence on the specific stability index, and for topsoils of previous samples of Ragdale, Hanslope and Evesham, the stabilities were more reconcilable when organic carbon contents were comparable. Work continues on attempts to relate physical variables to management experience. (North and Newell)

Relation of structural stability to soil parameters. Measurements of specific stability index, σ, for 23 soils were reported in *Rothamsted Report for 1975*, Part 1, 229. The relation of these indices to soil parameters variously proposed as agents of structural stability has been investigated by multilinear regression. The concentrations of organic carbon, clay, and calcium carbonate correlated significantly with the indices, those of iron and aluminium oxides did not. The significant parameters accounted for 75% of the total variance, and this proportion was not increased by regressing transforms of the parameters. The following equation, retaining only the significant parameters, accounts for 76% of the total variance:

$$\begin{aligned}\sigma/\mathrm{Jg}^{-1} = {} & (18{\cdot}3 \pm 4{\cdot}3) + (6{\cdot}0 \pm 0{\cdot}8)\ (\text{organic carbon}/\%) \\ & - (0{\cdot}28 \pm 0{\cdot}09)\ (\text{clay}/\%) - (0{\cdot}10 \pm 0{\cdot}07)\ (\text{calcium carbonate}/\%).\end{aligned}$$

The negative correlations with clay content and calcium carbonate were not expected. For most British topsoils, calcium carbonate concentrations are too low to produce contributions of practical significance. Further investigation of the clay contribution, undertaken with additional soils of clay content below the 16% minimum of the initial 23, failed to produce a positive correlation. (North)

Rate constants for soil dispersion. Ultrasonic soil dispersion may be interpreted as a bimodal process involving the rupture of both loosely- and tightly-bound clay-organic complexes (*Rothamsted Report for 1975*, Part 1, 230). Rate constants k_1, k_2, are ascribed to the loose and the strong binding, respectively, so that $k_1 \gg k_2$; there are assumed to be n_o clay particles per unit mass of soil, all of the same diameter, and n_t of them are released from aggregates during time t of ultrasonic agitation. Reaction kinetics predict

$$n_t = \tfrac{1}{2} n_o [2 - \exp(-k_1 t) - \exp(-k_2 t)] \qquad (1)$$

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The agitation times employed experimentally are such that $k_2 t \ll 1$, so that

$$n_t/n_o = \tfrac{1}{2}[1 - \exp(-k_1 t) + k_2 t] \tag{2}$$

Particle size uniformity implies that n_t/n_o is proportional to W_t, the measured weight fraction of clay dispersed.

Experimental values for W_t are well described by the equation

$$W_t = A + BR^E + CE \tag{3}$$

where A, B, C and R are fitted constants, and E, the applied dispersive energy, equals Pt, with P dependent on the ultrasonic power input. The similarity of equations (2) and (3) allows the determination of k_1 and k_2 in terms of the fitted constants, values for which were derived from measurements on the afore-mentioned 23 soil samples. The values obtained ranged from 0·030 to 0·142 s^{-1} for k_1 and from 0·00019 to 0·00165 s^{-1} for k_2; k_1 showed a negative correlation, and k_2 no correlation, with soil organic carbon content, confirming that higher organic contents strengthen the aggregate matrix and that the stronger bonds are mediated by specific organic macromolecules.

More fundamental than k_1 and k_2 are the activation energies, ϕ_1, ϕ_2, for disaggregation of the loosely and tightly-bound clay-organic complexes. These activation energies may be derived from k_1 and k_2 knowing E, and work to this end is in progress. (North)

Measurement of clay particle size distribution by photosedimentometer. The distribution of clay particle sizes may conveniently and rapidly be measured by a photosedimentometer, such as the Joyce–Loebl disc centrifuge. However, the normal experimental calibration of such an instrument is not suitable for clay materials, and a theoretical calibration has been derived. Particles of similar Stokes diameter d are detected optically with white light as they sediment in a centrifugal force field, and their concentration, c, is measured in terms of the turbidity of the suspension, τ, through the Lambert–Beer Law

$$c = d\tau/K$$

where K is the particle extinction coefficient. Unfortunately, for particles of $d < 2\ \mu m$, K depends strongly on both d and λ, the wavelength of the illuminating light. A numerical integration (following Allen, T., *Powder Technology* (1968), **2**, 133–140) was combined with calculations from Mie light scattering theory (Heller, W. & Pangonis, W. J., *Journal of Chemical Physics* (1957), **26**, 498–506) to take account of the spectral characteristics of the Joyce–Loebl quartz-halogen source and photodiode detector and thus permit the numerical calculation of K as a function of d for this particular instrument, and subject to the assumption that the clay particles behave as non-absorbing spheres.

The validity of this theoretical calibration has been investigated by comparing, for a group of kaolinite particles, 95% of which had equivalent Stokes diameters within 0·2 μm of their 0·6 μm mean, the particle size distributions as measured by the theoretically calibrated Joyce–Loebl detector and as measured by electron micrography (by courtesy of Dr. Meeten, City of London Polytechnic). The distributions were quite similar in shape, although the theoretically derived values tended to underestimate size by 0·05 μm. (North)

Tillage. Analysis of the 1975 measurements is complete, and results are being prepared for publication. In anticipation of 1977 measurements, the cultivator tine bars have been modified so that adjacent plots can be tilled without large discards; this will permit treatment replication. Work has proceeded on improving techniques for rapid survey of soil bulk density. (Brown and Dawes)

https://doi.org/10.23637/ERADOC-1-133

Soil respiration: laboratory. The rates of soil respiration, R_T, R_o, at temperature T and at reference temperature T_o are related:

$$R_T = R_o \cdot Q^{(T-T_o)/10}$$

where the parameter Q, the 'Q-ten factor', lies between 2 and 3. The relationship has import for field respiration, where the diurnal variation of soil temperature exhibits changes with depth both of phase and of amplitude, so that respiration integrated over a profile cannot be related, either instantaneously or over a time period, to a single soil temperature monitored at some convenient depth. Furthermore, because of the non-linear temperature dependence of R_T, the mean respiration rate averaged over several cycles of a sinusoidal temperature variation will exceed that predicted from the mean temperature value.

Equipment has been developed that permits both the imposition, in the laboratory, of steady and oscillatory temperature regimes on small soil samples and also the measurement of the resulting respirations. (Currie and Scott)

Soil respiration: field

Tank respirometers. In 1976, as in 1975, the tanks were uncropped, permitting further study of the change with time of the temperature dependence of soil respiration. Tank 8 has been uncropped and unchanged since installation, and the first four seasons' measurements indicated that the half-life of the more-readily decomposed organic grass residues was 3·1 years; this half-life has increased steadily during subsequent years. Tanks 5, 6 and 7 were planted with beans in 1974, and in 1976 respiration in these tanks was 50% higher than in the others. In 1976, June and July soil temperatures were significantly higher than in 1975, but 1976 soil respiration was higher only in June; in July, the effect of increased temperature was counteracted by a decrease in the amount of substrate suitable for respiration. (Currie and Scott)

Chamber respirometer. A new apparatus has been developed, consisting of a perspex enclosure that covers 150 cm^2 of soil surface. The enclosed air is stirred by a small fan, and as soil respiration proceeds, samples of air are withdrawn at one minute intervals for subsequent determination of carbon dioxide concentrations. The time-dependence of these concentrations permits calculation of the soil respiration rate at the time that the soil is covered, and the method of calculation avoids the need for leakage corrections. (Parkinson)

Response to irrigation of root respiration of spring barley. Measurements made at Little Knott in 1975 suggested that root respiration of barley was stimulated by additions of soil water (*Rothamsted Report for 1975*, Part 1, 231). In conjunction with the 1976 drought study at Little Knott (described in earlier sections of this report), and using the same techniques as in 1975, samples of soil air, from depths between 10 and 50 cm under selected plots of spring barley, were withdrawn daily throughout the growing season and analysed for carbon dioxide. Separate samples were withdrawn weekly for determination of oxygen concentration.

Smallest oxygen concentrations were usually, but not invariably, found at greatest depth, the minimum concentration, 17·5% by volume, was in the fully irrigated plot at 30 cm depth on 11 June. In the drier plots, at a particular depth, oxygen and carbon dioxide concentrations were negatively correlated.

In the fully irrigated plots, the carbon dioxide concentration at all sampled depths rose steadily from mid-May, one month after germination, to a maximum in mid-June, when

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stem extension had ceased, and remained near this high level until harvest, except that from early June, each application of water caused an increase in carbon dioxide concentration. A similar, but much more pronounced, respiratory response to irrigation was observed for the drier plots. In contrast, irrigations immediately after sowing and after harvest had little effect on carbon dioxide concentrations. This contrast suggests that the large respiratory responses to irrigation are mediated by the barley roots, and are not due either to a reduction by the irrigation water of the air-filled pore space or to an increase in the respiration of soil micro-organisms. This suggestion is supported by the calculated values of fluxes, as well as of concentrations, of carbon dioxide in 1975. The monitoring of soil carbon dioxide under field crops may therefore give a useful indication of root and plant activity that can be used to support irrigation management. (Pritchard and Scott)

Staff and visiting workers

T. Woodhead joined the department in July, having previously been Reader in Applied Physics at the University of Strathclyde, and in October P. J. Zemroch came from the Department of Statistics, University of Leeds, to join both the Statistics and Physics Departments. M. Derry left in September to take up social work. J. Connell, P. Dominy, S. Newell and M. Sayers all spent several months in the department as sandwich course students, and S. Jackson a few weeks as a vacation worker. Dr. G. Buchan of the Macaulay Institute for Soil Research was a voluntary worker in the soils section during part of August, and Mr. W. de C. Jeffers (Caribbean Meteorological Institute), Mr. J. P. Fonseka (Tea Research Institute, Sri Lanka) and Mr. M. A. Khan (Central Cotton Research Institute, Multan, Pakistan) were each attached to the department during some part of the year.

During 1976 the decision was taken that staff members of the ARC Unit of Soil Physics in Cambridge would be transferred into the Physics Department in Autumn 1977. Plans have been prepared for the modification of part of the Bawden Building to suit the particular requirements of their equipment.

Publications

Research Papers

1 Bainbridge, A. & Legg, B. J. (1976) Release of barley-mildew conidia from shaken leaves. *Transactions of the British Mycological Society* **66**, 495–498.

2 (Crowther, J. M., Dalrymple, J. F.), Woodhead, T., (Coackley, P. & Hamilton, I. M.) (1976) The application of statistical modelling to waste water treatment. *Proceedings of Conference on Systems and Models in Air and Water Pollution*. Institute of Measurement and Control, London. pp. 6.1–6.10.

3 North, P. F. (1976) Towards an absolute measurement of soil structural stability using ultrasound. *Journal of Soil Science* **27**, 451–459.

4 Penman, H. L. & Long, I. F. (1976) Profiles and evaporation. *Quarterly Journal of the Royal Meteorological Society* **102**, 841–855.

5 Pritchard, D. T. & Ormerod, E. C. (1976) The effect of heating on the surface area of iron oxide. *Clay Minerals* **11,** 327–329.

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