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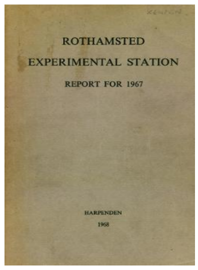
ROTHAMSTED RESEARCH

Rothamsted Report for 1967



Physics Department

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PHYSICS DEPARTMENT

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Agricultural meteorology

The primary task of agriculture and forestry is to fix solar energy in ways that make it usable elsewhere, and later, as food or fuel, or as non-consumable products that provide shelter, clothing or other essential amenities. A survey of world efficiency in fixing solar radiation (1.7) shows that the average achievement in the under-developed countries of the world is only about one-fifth of the average achieved by the industrialised nations of North-west Europe, that this better average achievement is only about one-third of what is obtained in experiments or by the best of good commercial farming, and that occasionally, for short periods within the growing season, plants fix solar radiation with an efficiency two or three times as great as the whole-season average rate. Much of the work of the Station is directed towards getting the average nearer the best in British farming, and though the Botany and Physics Departments contribute to this directly, there is a further contribution from them in their attempts to find out how the best yields can be improved. This involves research in plant physiology, and, like much of the rest of the world, the Physics Department now uses the technique of Growth Analysis developed by the Botany Department to complement its own work on the response of the plant to its environment.

Many preceding departmental reports have described the development of techniques for measuring the environment, above and below the surface of the soil, have summarised the results of measurement, with analyses in a physical or meteorological context that needed no more than one or two days' records to prepare a satisfying coherent picture (1.3), and latterly have included measurements of growth and development of the plant. With this extension, the need for automatic sensing and computor processing of the physical elements is steadily becoming more urgent, because the significant time interval that matters now is one long enough to take in at least a complete phase in plant development, and preferably a whole growing season.

Experimental background to field work. On Great Field II there is an irrigation experiment in three main series, of which two are subdivided into plots on which variants in terms of management are imposed, with conventional randomisation and replication: results are at the end of this report. The third has only two plots—the so-called "macro-plots"—which are almost big enough for reliable micro-meteorological observations, and they differ only in that one is irrigated liberally but short of wastefully, while the other is left to Nature to water: in 1967, for the first time since we started using them, summer rainfall was sufficiently inadequate to produce a major difference in the water régimes of the two plots, with corresponding detectable differences in the micro-climates and in the plant physiology of growth. The crop was kale, and though it suffered grievous

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competition from weeds in its early stages, two thorough hoeings and a weed-killing spray produced two fairly even stands, for which comparisons are meaningful. One of the reasons for choice of kale as test plant was to give the opportunity of working well into the winter, and a few severely cold days and snow early in December were very welcome—scientifically! In addition, plants from this field were transplanted in the respirometers at Wrest Park, Silsoe, and, with obvious need for caution, comparisons of behaviour at the two sites may help in understanding what happened at each.

Equipment on macro-plots

(*i*) ***Micro-climate.*** With spacings determined by the resolution thought to be desirable there were sensors above and within the crop canopy, and in the soil (1.5). Common to both irrigated and non-irrigated plots were units to measure: air temperature and humidity, wind speed, leaf temperature, soil temperature, surface wetness of leaves, soil water content (to 150 cm; neutron technique). In addition, on the irrigated plot only there was a wind-direction recorder, a horizontal array of temperature and humidity sensors at constant height, a Hirst balance and a Kipp radiation recorder. (Long and French)

(*ii*) ***Radiation, carbon dioxide and evaporation.*** Evaporation (transpiration gauge), net radiation (above and within the canopy), soil heat flux and reflection coefficients were measured (1.10). Carbon dioxide profiles were measured at eleven heights, and a similar infra-red gas analyser was used on the same samples to measure water-vapour content. As a supplement to the point temperature measurements ((*i*) above), a 1-metre wide array of thermocouples was used to get a line average. A set of solarimeters with internationally recommended filters was set up to study the spectral distribution of solar radiation. (Monteith and Szeicz)

(*iii*) ***Plant physiology.*** The diffusion porometer was in constant use, measuring stomatal resistance of chosen leaves on selected plants, giving records of diurnal changes, and changes with leaf age and crop height. Dry matter and leaf-area index were measured weekly, and also distribution of leaf area with height. (Parkinson, Rowse, Beatrice Scorer, Whittet and Aston)

Laboratory equipment. The controlled environment apparatus to measure transpiration, assimilation and respiration of leaves on plants from the macro-plots was improved to give easier and more efficient use. (Parkinson)

New, or redesigned, equipment began to emerge from proving trials. It includes a 50-channel automatic pF meter (psychrometer principle), mainly intended for measuring water potentials in plant material, but it will be used for soils too: a description is in preparation. An old transpiration balance, used by Monteith 14 years ago, was redesigned and rebuilt: it will now take a load of 20 kg and, at best, will respond to ± 5 mg change in

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weight. An automatic potometer records the uptake of water by a cut stem or of a plant grown in water-culture solution. In the course of pilot experiments an excised kale leaf exposed to a severe constant transpiration load showed a cyclic pattern of water uptake, with a period of about 20 minutes, and with variable transpiration load, the weight of the leaf changed with the expected phase difference. (Rowse)

Micro-climatology. Differences between the macro-plots, directly attributable to irrigation, became more apparent as the season progressed (the first important rain occurred about mid-August). The evaporation rate from the irrigated plot (neutron meter) was the greater in this period, and somewhat exceeded the value calculated from the Penman formula—based on the radiation record taken at the laboratory. Some close detective work showed that this routine instrument has a small persistent negative error and, through the integrating mechanism, this produces a total underestimate of incoming radiation of perhaps 3% on a sunny day, and perhaps 10% on a dull day: the calculated values of evaporation should be 5% (or more) greater than so far estimated.

Some anomalous behaviour in the air flow inside the kale canopy (an unexpected degree of ventilation just above ground level) was explained when a test showed that at the edges of the crop the air-stream flowed directly into and out of the crop rather than being diverted over the top. Here is another "small plot" effect—quantitative importance not known—that might affect the results of work on pests or diseases. The effect becomes rather more intense as the crop ages, because defoliation at the lowest levels produces a more open space just above the soil surface, and it may have a significant effect on water vapour and carbon dioxide transfer in the lower canopy (1.11).

When evaporation ceases at the end of a sunny day an individual kale plant regains lost turgidity throughout the night. The amount so taken from the soil may be 40 cm^3 or more, and on suitable nights 30 cm^3, or more, of dew may be added. The combined night-time accession is usually evaporated within 6 hours of sunrise.

First (and few) observations in frost indicate that the plant tissue of kale freezes at a lower temperature than that of any other crop so far studied. (Long)

After a very wet May the soil moisture deficit steadily increased to over 4 in. by the end of August. Rain gauges set up round the neutron-moisture-meter access tubes confirmed what had been inferred from previous analyses—that it is unsafe to use the average irrigation intensity for the whole plot in calculating the water balance for a particular point. The discrepancy was technically rather serious for the kale plots, and although the sprayline arrangement was modified to give a more uniform spread, it is still not good enough. (French)

Radiation, carbon dioxide and growth. The crop emerged about mid-May and, after cleaning operations in June, growth was rapid from the beginning of July; the first irrigation was applied on 7 July, and the second on 17 July. Even with this established difference in water régime, the stomatal

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resistance on both plots was about the same and changed only slightly from dawn to about 10.00 h, but thereafter it increased on both: by late afternoon the resistance on the unirrigated plot was twice that on the irrigated plot, with a corresponding difference in transpiration rate, and, presumably, in assimilation rate. From 20 June to 31 August the transpiration gauge estimates of evaporation rates were 5·1 mm per day (irrigated) and 3·4 mm per day (unirrigated), but though the sign of the difference is beyond question, the sizes are very uncertain. The average net radiation for the period was 190 cal cm^{-2} day^{-1} ($\simeq$3·2 mm per day evaporation), and the gap between 5·1 and 3·2 is much too big to explain meteorologically: during recent years we have become increasingly dubious about the reliability of transpiration gauges for anything other than a short crop such as clipped grass, and we intend discarding them as research tools.

The seasonal pattern of growth is best shown by Table 1. Ignoring

TABLE 1

Growth of kale, 1967

Period	Unirrigated G	L	G/L	Irrigated G	L	G/L
20–30 June	9·0	1·3	6·9	8·0	0·7	11·4
1–10 July*	23·0	2·8	8·2	19·5	1·9	10·2
10–20 July*	17·0	4·2	4·0	30·0	4·2	7·2
20–30 July	6·0	4·2	1·4	9·5	4·8	2·0
30 July–9 August	3·5	3·8	0·9	9·0	4·5	2·0
9–19 August†	29·3	4·5	6·5	8·4	5·0	1·7
19–29 August*	12·5	5·0	2·5	7·8	4·3	1·8
29 August–8 September	3·8	4·9	0·8	6·3	4·1	1·5

* Irrigated.
† 1·13 in. rain 12–19 August.

G = growth rate, g m^{-2} day^{-1}.
L = leaf area index.

sampling errors, up to 9 August there was a clear gain from irrigation; independent of sampling errors, there was an extraordinary flush of growth between 9 and 19 August on the unirrigated plot, bringing the two totals to near equality. A similar rapid response to rain occurred on sugar beet at Woburn in 1955, but attempts to reproduce the effect in controlled experiments failed.

Leaf expansion rate was 11% per day in June, declined slowly to mid-July, and thereafter rapidly, to about 1% per day. Although at best the leaf-area index reached about 5, the top unit area absorbed about 64% of the incoming radiation: half the leaf area was in the top third of the canopy.

A small part of a lot of detailed analysis, nearly all of which still has to be done, can be given no more than summary statements. The atmospheric resistance to transport (water vapour and carbon dioxide) is not very dependent on wind-speed: the faster the wind, the smaller the roughness coefficient. There is a complex feed-back (also detected in previous years) between soil-moisture deficit, stomatal resistance and saturation deficit of the air: when it is sorted out it may be possible to use ordinary weather records to calculate *actual* rates of evaporation as well as potential rates—as is our routine. Respiration rate seems to be faster in drier soil. On three occasions about 5% of the total evaporation came from the soil. On 7

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August, on the unirrigated plot, the upper leaves in the first six 10-cm layers transpired at the same rate per unit leaf area: after rain, on 17 August, the rate for the layer 20–30 cm was twice that in the top 10-cm layer. There was no such uniformity or contrast in the carbon dioxide uptake: all the photosynthesis took place in the top half of the canopy—in August the 10–30-cm layer took up 60%, and in September, 90% of the total, and in general this layer, in terms of uptake per unit area, was three to four times as efficient as any other part of the crop. (Monteith, Szeicz and Long)

Plant physiology. The physics of assimilation can be expressed in two ways: first as an efficiency of fixation of solar energy in the form $P = \varepsilon I$, where I is sometimes the total short-wave energy intensity, and sometimes is an estimate of the visible component, I_v, where $I_v/I \simeq 0{\cdot}45$. The second treats the system as analogous to an electrical circuit in which a potential difference (carbon dioxide concentration difference) produces a current (carbon dioxide flux) through a series of resistances. Three resistances recognised so far are: (1) from the ambient air to the leaf (atmospheric resistance, r_a—also a resistance in the water-vapour flux path); (2) into the leaf (stomatal resistance, r_s—also in the water path), and a mesophyll resistance, a rather vaguer component to cater for movement from the sub-stomatal cavity to the chloroplasts, but not appearing in any expression for water transfer. With an allowance for the rate of the carboxylation reaction, a somewhat complex expression can be written down incorporating both the physical approaches: it contains several unknown quantities, some of which can be measured directly or estimated independently (e.g. r_s can be measured by the diffusion porometer: r_a, in the field, can be calculated from wind-velocity profiles) and others come out of laboratory measurements of two kinds. At constant external carbon dioxide concentration, ρ, the light response curve of P against I is obtained. Extrapolated back to $I = 0$, the slope there gives $\varepsilon_{max.}$: if necessary, forward extrapolation to a limiting $P_{max.}$ gives a combination of some of the other unknowns. At constant light intensity the carbon dioxide response curve gives the sum of two of the resistances from the slope at $\rho = 0$, and another combination of unknowns at an upper limit of a new $P_{max.}$. All unknowns are now determinable.

Most of the work was done on kale leaves, with some on stems and petioles. Again only in summary, $\varepsilon_{max.} = 0{\cdot}157 I_v$ or $0{\cdot}07 I$, which is very close to the theoretical limit in feeble light. The value varied with depth in the canopy (usually, but not always, greatest at the top). Resistances also varied with position and age of leaf and, again with exceptions, increase in resistance coincided with decrease in efficiency. Plants from irrigated plots respired faster than those unirrigated. (Parkinson)

The parallel problem of transpiration is slightly simpler because the resistances are fewer. Possible restriction of both assimilation and transpiration could come from management of r_s, the stomatal resistance, with some prospect that the relative effect on growth would be less than on transpiration. Trials with some silicone compounds—sprayed on—gave the opposite result: the resistance to carbon dioxide uptake seemed to

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increase more than the resistance to transpiration. Other forms of application, and other possible anti-transpirants, will be tried. (Legg and Parkinson)

Respiration. After the 1966 experience the soil respirometer equipment at Wrest Park was modified to include an automatic self-servicing, self-recording oxygen supply that kept the gas concentration over the soil surface (and under the sealed lid) near 21%, giving fine detail within days, and a somewhat cruder system of monitoring gave daily totals of carbon dioxide removed. There were thermometers at 0, 10, 20 and 40 cm below the surface of the soil, and the water seal at the bottom of each of the six tanks (three cropped, three bare) also kept the plants adequately supplied with water. For all six tanks mean daily air temperature (approximately equal to mean soil temperature) proved to be the main moderator of soil respiration. The crop part of the experiment began effectively in mid-July, when the kale plants were finally sealed into the lids. The ranges of daily oxygen requirements, in litres per square metre of soil surface, were: uncropped soil, 2 at 2° C in February; 12 at 17° C in July; 1·5 at 5° C in November; cropped soil, 18 in July, 3 in November, at the same temperatures. The average ratio cropped/uncropped from July to November was near 2·5, and in this period of 18 weeks the cropped soil used oxygen at a rate of 140 cwt acre^{-1} and evolved carbon dioxide at a rate of 192 cwt acre^{-1}. These are extraordinarily large values, very much greater than the expected amount of dry matter in the crop when harvested, but they have a parallel in the measured carbon dioxide gradients in and above the crop measured during the Rothamsted field experiment. The respiratory quotient (volume CO_2 evolved/O_2 used), calculated for weekly periods, rarely moved far from unity: the 18-week average from above corresponds to almost exactly unity. (Currie)

The Rothamsted equipment on the macro-plots included units for measuring carbon dioxide gradients in and above the canopy from which downward fluxes of the gas could be calculated. For three short periods analysed in detail, with rate of dry-matter accumulation known from crop sampling, the approximate carbon dioxide balance indicates respiration rates of the order of 1–2 g m^{-2} h^{-1}, or about 12–24 litres of carbon dioxide per square metre per day in August (Szeicz). Measurements on single leaves in a controlled laboratory environment in mid-July gave a field equivalent respiration rate of 1 g m^{-2} h^{-1} (Parkinson). Without prejudging what will come out of the analyses of all the season's results, it seems clear that there is a prospect of some degree of consistency in the returns from three completely different experiments, with respiration rates of the same order as the rates of crop growth. (For conversion: 1 cwt acre^{-1} dry matter $\simeq$ 18 g m^{-2} CO_2.)

Soil physics

Aeration and optimum soil environment. All the effort was put into the use of the respirometers at Wrest Park, and the main quantitative facts are set out above. Within the totals given there is some interesting detail. From

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weekly averages the respiration rates fit $R_T = R_0Q^{T/10}$, and for $\delta T = 10$, $Q \simeq 3$, but the value of R_0 decreases by about $\frac{1}{3}$ from the first to the second half of the year. On a shorter time scale respiration rate tends to lag behind temperature change by about 2 days: though there are some physical reasons (general, or peculiar to the experimental arrangement) why this could happen, the main effect probably has its source in temperature effects on the numbers in the micro-population. (Currie)

Soil water. Water movement has three important aspects: how does water get into dry soil; how does it get out of wet soil; how does it redistribute itself in the processes? The key to the first two questions is in the answer to the third, and two formal approaches are open. One can work in terms of water potential gradients (pF = $\log_{10}$ of potential) and a hydraulic conductivity, or in terms of moisture content gradients (volume/volume) and a hydraulic diffusivity. For theoretical studies the first is much easier to handle: for practical applications the second is preferable. The link between them is the slope of the pF curve, and trustworthy values can come only from careful measurements of pF and water content.

Measurements were made on eight soils by suction, osmotic, psychrometric and desiccator techniques, drying over the range pF 2·0–7·3, and wetting back to pF 4·0. The osmotic technique is relatively new, and work on it, started at Rothamsted, is being continued in Canberra. The source of the variable potential is a solution of polyethylene glycol, and samples of soil aggregates in closed cellulose bags suspended in an ocean of stirred solution come to moisture equilibrium in a few days, and from a calibration curve for the glycol solution the equilibrium matric potential can be found. Tests on four soils, at nine points between pF 2·6 and 4·5, agreed well with results using other standard techniques.

In the course of measurements of diffusivities, pairs of soils were compared, one with a long record of heavy dressings of FYM, the other without. At any water content between pF 2 and pF 6 the diffusivities were about the same for each soil of a pair, in spite of some detectable changes in other physical properties. Six pairs (from Rothamsted, Woburn, Saxmundham and Wellesbourne) showed that the FYM had decreased particle density by 2–4%, had increased crumb porosity by 12–24% and had increased water held at crumb saturation by 15–30%. (Rose)

Good progress was made on the uptake of water (1.9) and on the drying process (1.8). Assuming alternative conditions for root distribution, depth of soil, intensity of transpiration load and source of resistance to transpiration, 2^4 theoretical curves of actual *v* potential transpiration were computed, using values of diffusivity measured by F. Wangati. Every form of curve found in experiments appears as one of the sixteen, and it may be that long-standing arguments about the "availability" of soil water can be toned down. Some progress has been made on a generalised theory of hydraulic conductivity, using no more than the pF curve as datum; first tests on the experimental results of Rose and Wangati on loam soils were very good, but extension to a coarse sand (with conductivity about 10^5 times as great as for the loams) was out by a factor of three or more—which is not good enough. (Penman)

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Physical chemistry of clays. Apart from its obvious importance in fertiliser movement and availability, the surface electro-physics of clays affects the mechanical behaviour of soils, swelling leading to decreased permeability, difficulty of management, capping and cracking on drying, and it may be that failures of minimum tillage techniques in clay soils can be tracked back to imbalance in phenomena that affect flocculation and deflocculation. It is part of farming experience that replacing calcium and magnesium ions by sodium, even in the absence of a deflocculating agent, can lead to difficulties. In previous work on dilute clay suspensions there has been conflict with the results of Dr. H. van Olphen; the present work uses his technique with one variant. He allowed 1 minute for the suspensions to come into equilibrium: we give them an hour. As the conflict remains, the time factor may be significant, but even 1 hour seems rather short in the time scale of soil processes.

Clays can be deflocculated in two ways. The positive charge on the edge can be neutralised by a suitable anion, so eliminating edge-to-face attractions, or by increasing the repulsive force (face-to-face) by replacing polyvalent exchangeable cations already there by sodium ions in excess of those in the ambient water. Adding sodium to the outside solution will counteract the effect, and this is the basis of the technique. A clay suspension is made up in a standard way, the "test" deflocculant and varied concentrations of sodium chloride are added, and then the suspensions are allowed to stand, with occasional shaking, for 1 hour before centrifuging for 5 minutes at 1500 rpm. Within the range of sodium chloride concentrations there will be one at which maximum flocculation action is first attained, and the experiment sets out to find the amount of tested deflocculant needed to attain this maximum action. The scale of conflict can be seen from the theoretical prediction that in some conditions about 2·5 milli-equivalents per litre of an efficient deflocculant should be required: van Olphen found about 100 m.eq/l of sodium polymetaphosphate were needed. Present results confirm the theoretical figure, although the concentration for maximum flocculating efficiency is greater than van Olphen found, but this greater value has two supporting pieces of evidence. Approximately the same sodium chloride value is obtained (at 550–600 m.eq/l) whether the deflocculant is added as polymetaphosphate or as citrate, and work elsewhere on the changes in X-ray spacing of a flake of bentonite shows a sudden jump from 19 to 30 Å as the dilution of the ambient solution of sodium chloride passes through 500 m.eq/l.

The conflict about the facts has a parallel in conflicting interpretations, and a summary statement, fair to both sides, is impossible. (Cashen)

Irrigation

Rothamsted. The amounts, at about 1 in. per application, were: barley, 4·3 in.; beans, 5·0 in.; kale, 3·0 in. The second irrigation of the barley and the beans (end of June) was nullified by heavy rain soon after: the kale got less than the other crops because it was a late-sown crop, and did not produce any real cover until the end of June.

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The important part of the results for kale is in Table 1. For the other crops the main results are:

	Irrigation	Grain (cwt/acre)
Barley	None	38
	2·3 in. before 24 June	41
	2·0 in. after 8 July	35
	4·3 in.	38
Beans	None	33
	2·0 in. before 24 June	37
	3·0 in. after 8 July	39
	5·0 in.	39

(French and Penman)

Woburn. As in 1966, the crops were spring wheat and potatoes, with a CCC and fumigant treatments for the wheat (Humphries, Botany Department; Slope, Plant Pathology Department) and a very complex set of fumigant and variety treatments for the potatoes. (Jones, Nematology Department)

The main result for the *wheat* is that 4·0 in. of irrigation increased average grain yield from 41 to 49 cwt/acre, and average straw yield from 46 to 52 cwt/acre. Within the treatments one plot gave 59 cwt/acre of grain and 72 cwt/acre of straw (both at 0·85 dry matter), giving a total botanical yield of about 5·5 tons of dry matter/acre.

Because of the deliberate choice of unsatisfactory conditions for *potato* growing, plot yields differed greatly. The best result, coming nearest to what a commercial farmer might look for, was an increase from 12·4 to 15·1 ton/acre for 4·2 in. of irrigation. (Thorold and Penman)

Staff and visiting workers

There were important staff changes. J. L. Monteith left to become Professor of Environmental Studies, School of Agriculture, Sutton Bonington and D. A. Rose started his two-year Fellowship in Australia. N. J. Brown was transferred from Wrest Park, Silsoe, to work on the physics of soil tillage, and B. Legg, appointed earlier, joined after a period of voluntary service overseas. Dr. T. A. Bull returned to Queensland. Miss Beatrice Scorer (Cambridge), Mr. A. R. Aston (Illinois) and Mr. D. C. B. Whittet (Dundee) spent several weeks helping in field and laboratory.

H. L. Penman travelled to the Lebanon for the Centenary Celebrations of the American University of Beirut: the Symposium ended on its first day because of war in the Middle East.

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