ROTHAMSTED RESEARCH

Report for 1964

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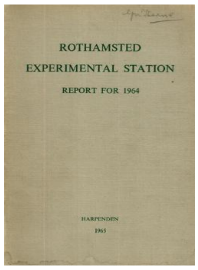

Physics Department

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PHYSICS DEPARTMENT

H. L. PENMAN

Doreen Armstrong left in the autumn to get married. J. A. Currie attended the Soils Congress in Bucharest, and D. A. Rose presented a paper at the RILEM Symposium in Paris: both took the opportunity to visit nearby research institutes. J. L. Monteith and H. L. Penman gave papers at the International Botanical Congress in Edinburgh, and also contributed to several other symposia. H. L. Penman led the British delegation at the Paris inter-governmental meeting of UNESCO to draw up the programme for the International Hydrological Decade, 1965–74.

Dr. R. D. Jackson (U.S. Water Conservation Laboratory, Tempe, Arizona) spent three months with us, and Mr. F. Wangati (East African Agricultural and Forestry Research Organisation) came in September to work on agricultural meteorology. Before and after the Edinburgh Congress, Prof. H. N. Barber, F.R.S. (Botany Department, University of New South Wales) spent several weeks here, shared mainly between Physics and Botany Departments.

Background. Some years ago the work of the Physics Department was described as the search for "knowledge and understanding of the physics of the environment of the growing plant, in the expectation that they will lead to possibilities of prediction, control, and exploitation". For convenience in description the two parts of the environment are usually considered separately—as Soil Physics and Agricultural Meteorology—but the growing plant links both, very obviously in water transfer, and almost as obviously in carbon dioxide exchanges. Only one part of the Soil Physics can be separated from the rest without distortion, namely the work on the electrical charges on clays. This is basic to nearly all soil science, from pedology (weathering of clays), through agricultural physics (soil structure) to soil chemistry (base exchange and acidity). A review of recent Rothamsted work on this topic appears elsewhere in the report (G. H. Cashen, p. 291), and the remainder of the year's work can be conveniently surveyed as a whole.

The "whole" can be set down simply, without too much inaccuracy. A plant grows because the solar radiation it absorbs provides the energy for the photosynthesis of carbohydrate, using the carbon dioxide of the external environment as the main raw material. The gas has to get into the leaves, and it does so through stomata normally open in daylight and closed in the dark, but daytime closure may occur because of water shortage. To maintain enough water in the leaves there must be enough in the soil: when this condition is satisfied the open stomata provide outward leakage paths for water vapour—the plant "uses" water as it grows—and about one-third (or more) of incoming solar energy goes into this evaporation process. The adequacy of soil water depends on the volume of water per unit volume of soil, and partly on the ability of the soil to transmit water in

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response to the suction gradient set up by the desiccating action of the roots. Such transmission may sweep nutrients along with it—one way of feeding plant roots—or there may be diffusive transfer of nutrients (in otherwise static water) in response to concentration gradients established when the roots take up ions. While it grows, the plant uses some of its own material as fuel, and the end-product of this process of respiration—carbon dioxide—appears in the soil and in the atmosphere. The soil component eventually reaches the atmosphere, in diffusive exchange with air, and root activity (or any other biological activity in the soil) demands an exchange rate fast enough to keep the concentration of carbon dioxide small and the oxygen concentration large. The carbon dioxide then becomes part of the gaseous environment of the plant leaves, available for re-assimilation. The rate of uptake depends on: (i) the ability of the stomata to transmit the gas (so bringing in the concept of a stomatal "conductivity" or a stomatal "resistance"); (ii) the strength of the ultimate sink for the gas, effectively within the chloroplasts where the solar radiation is absorbed, and dependent on the radiation intensity there (with a daily cycle, and day-to-day changes within a seasonal cycle); (iii) the combined strength of the sources and the turbulent exchange processes that simultaneously transmit atmospheric quantities (heat, water vapour, carbon dioxide and momentum, with parallel concepts of atmospheric "conductivity"—the eddy diffusivity—and atmospheric "resistance"). It is these exchange processes that build up the physical environment of the plant, and though they are not all of comparable importance in their first-order effect on the growth rate of healthy plants, some can have important second-order effects, and for plants affected by disease or insect pests they may determine the severity of attack.

It is part of the task of the department to measure as many of these components as possible, and most of what we measure is continuously recorded throughout the summer growing season. Hitherto, analysis of records has been restricted to short periods of a few days, for use in tackling a particular physical problem in which plant growth is not a factor: the descriptive part of one such intensive task is, in effect, the physics of a day in the life of a barley crop (1.8).

Soil water. "Prediction, control and exploitation" are already possible to an acceptable degree of accuracy in some parts of agricultural hydrology but not in others. The basis of our method of estimating water requirements of crops is an energy balance, and to a very good first approximation the rate of water use when water supply is non-limiting is equal to the net radiation in the same units. A brief general survey (1.3) shows that what we know to be true at Rothamsted is true elsewhere in the world for a wide range of crops in climates free from major advective effects: a hot, dry surrounding area provides an additional source of energy for evaporation. Continuing the field trials to see how dry the soil can become before growth is checked, an irrigation system was installed on the Rothamsted farm during the early summer. For varied reasons the experimental programme was restricted to two crops—grass and potatoes—and a summary of results is at the end of this report. (Penman) Among the observations made were

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estimates of the water content of the soil profile (0–100 cm) using the neutron moisture meter. These showed Fescue grass using water more rapidly than Timothy when not irrigated, with the maximum difference at the end of August, when the soil moisture deficits were 5·8 and 5·2 in. respectively. From 22 April to 21 September the rainfall was 8·2 in. and the calculated potential transpiration was 14·7 in.: the potential deficit on 21 September was therefore 6·5 in. Allowing for a (calculated) deficit of 1·0 in. at the date of the first set of neutron meter observations, the mean of the observed deficits in the non-irrigated plots was 6·5 in., an exact agreement that is misleading for two known reasons (but acting in opposite senses). After 3·0 in. of irrigation the potential deficit on the watered plots was 3·5 in.: the mean of the observed values was $1{\cdot}0 + 4{\cdot}7 = 5{\cdot}7$ in. Non-uniform watering could account for part of the discrepancy, but most of it is thought to arise because the plots were too small. (Long and French)

Water movement. Previous work on the movement of water (as vapour and as liquid) in relatively dry soils was described at an international conference (1.12). (Rose) As a bridge to new work on the movement of nutrients by and in soil water, some experiments copying what Marshall and his colleagues did in Australia years ago gave the same result (1.7). When a moist (unsaturated) soil with initially uniform water and salt contents has a temperature gradient imposed on it, the water and salt are redistributed: water leaves the hot end to accumulate at the cold end; salt leaves the cold end to accumulate at the hot end, presumably swept along in a counter-current of liquid water opposing the distillation process. The main return to us is in helping to clarify ideas on the transfer processes: for Dr. Jackson it may have more practical value in the salt and water problems of Arizona. (Jackson, Rose and Penman)

The most difficult range of water content for movement studies is in soil somewhat drier than field capacity but wetter than in the experiments by Rose referred to in 1.12. This is the range of agricultural importance, and a fresh attack is worthwhile, both as part of the story of water available for transpiration and as part of the story of nutrient uptake. Long columns of soil ("semi-infinite" for formal analysis) were set up, uniformly packed and initially uniformly moist. After a period of drying at one end, the columns were cut into short sections and the water content of each measured. From the water content/distance curve a series of diffusivities can be calculated. First results show what everyone knows, that the diffusivity decreases as the soil dries, and, more interesting, that there is a minimum and a subsidiary maximum in "dry" soil, a result predicted by Philip from Australia.

Here all the soil is getting drier, but there are important technical conditions in which part or all of the soil is getting wetter, and it may be helpful to consider a drying diffusivity and a wetting diffusivity that are significantly different at a given water content. Almost 40 years ago, Haines, at Rothamsted, worked out the theory of hysteresis in soil-water equilibrium: we expect this to be reflected in the dynamics as well as the statics of soil water. It is known that, at a given moisture content, the electrical

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resistance is greater when the soil is being dried than when it is being wetted, and it is a fair inference that the hydraulic resistances will show a difference in the same sense, i.e., the conductivity of a wetted soil will be greater than that of a dried soil at the same water content. (Rose)

Water measurement. At the end of the dry summer of 1964 more than 100 undisturbed soil samples were taken near the sensing tube for the neutron moisture meter, and their water contents measured. This amount was always less (by 2–4%) than at the same depth as measured by the neutron device, suggesting that hydrogen bound in the soil (other than as water) is registered by the neutron scattering method. (Rose and French)

Aeration. Over the past few years the seat of aeration problems has been shown to lie in crumb micro-structure, not in the soil as a quasi-homogeneous mass. Techniques for direct measurement of the relevant micro-structural parameters do not exist, and the indirect techniques in use are only possible with the apparatus working at the limit of its sensitivity. The first reaction is to try to improve sensitivity, and a lot of effort has gone into this.

In preparing samples for experiment two things have happened unexpectedly. Weekly diffusion measurements were made on soils stored meanwhile in desiccators over solutions of increasing vapour pressure. This way of wetting a soil is exasperatingly slow—it took almost a year to get from dryness to near saturation—and changes occurred during the period. To restrain biological changes a drop of xylene was put into each desiccator, but it may have failed in its purpose. When samples had reached equilibrium, and were yet unsaturated, attempts to complete saturation by adding drops of water failed: the crumbs were perfectly waterproof. The second effect was produced by the unavoidable alternation of evaporation and condensation during experiments and storage: salts moved, producing a surface inflorescence. With this evidence of slow secular change of structure during the storage of moist soil it is not safe to identify small differences in laboratory behaviour with equal differences in field state at sampling time, which might be several months earlier. Nevertheless, the main conclusion from the previous work was confirmed: in comparing soils that a farmer would classify as having "good" structure and "bad" structure, the good is characterised by having more facile gas movement in its crumbs when they are dry, and the contrast is even greater as the crumbs approach saturation (1.6).

One of the other possible mechanisms of aeration is being re-examined, although diffusion is known to be sufficient. Atmospheric pressure changes could act to the same effect and, although it is easy to show that large changes are not frequent enough to be sufficient, the small but frequent changes associated with turbulent air movement might make some significant addition to what is done by diffusion. Measurements show that they do accelerate the exchange of gas between atmosphere and soil, and in one experiment on a sample with a surface crust the transfer occurred when the crust was almost impervious to diffusive transfer. Such an effect might be important for seedbeds and during the early life of crops. (Currie)

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Agricultural meteorology—general. The main job for the physicist is to sort out interactions of water supply, energy supply and carbon dioxide supply. When the water is there, in non-advective situations, the rate of water use is approximately equal to the net radiation flux: in other conditions this flux is shared between sensible heat transfer and evaporation, and the ratio of the two—Bowen's ratio—is a useful parameter for studying the effects of atmospheric and plant variables on the heat and water exchanges (1.1). One of these plant variables is the stomatal resistance, a quantity that can be estimated indirectly from measured evaporation rates (now almost a routine part of our data processing); others elsewhere are trying to measure it more directly; and we are again trying to calculate it from stomatal dimensions and populations. A general review (1.2) of the three-fold interaction shows the value of a concept of workers in the Netherlands, that there is a potential rate of photosynthesis representing the maximum possible rate of dry-matter production for a given set of conditions. These are: daylength and daily insolation; the light response curve of the leaves of the particular crop; the leaf area; and the amount of radiation that penetrates to different levels in the crop canopy. It is worth noting that calculated potential rates far exceed normal field rates of growth, and the central question in agricultural meteorology is to find out why there is such a gap, and how far it can be filled by improved management, husbandry or plant breeding. (Monteith)

Resistance. The fluxes of water vapour and carbon dioxide are currents maintained by potential gradients across chains of resistances. When the current is in quantity per unit area per unit time, and the potential is quantity per unit volume, the resistance is a length (cm) divided by a diffusion coefficient ($cm^2\ sec^{-1}$), i.e., has the dimensions of $sec\ cm^{-1}$. In the turbulent atmosphere the diffusion coefficient is the eddy diffusivity, the same for both vapour and gas, and hence the resistance is the same for both: in still air (i.e., within the leaf and very close to its surface) the diffusion coefficients are not equal, and the carbon dioxide resistance is $0{\cdot}26/0{\cdot}14$ times the water-vapour resistance over the same path length.

In transpiration, water evaporates from the cell walls and first encounters a stomatal resistance in reaching the leaf surface. For *a single leaf* this resistance is often between 1 and 2 $sec\ cm^{-1}$ when the stomata are fully open. The next resistance depends on leaf size and shape, and on ventilation: when wind speed is between 1 and 5 $m\ sec^{-1}$ the aerodynamic resistance is usually about $0{\cdot}2$–$0{\cdot}4$ $sec\ cm^{-1}$, considerably less than the stomatal resistance. Hence for any fixed values of radiation, temperature and humidity, the rate of transpiration for a single leaf is governed by stomatal resistance and is almost independent of wind speed.

Analysis for *a crop canopy* (1.9) yields two resistances, formally similar to those for a single leaf, namely, a surface resistance depending on the stomatal resistance of individual leaves and on total leaf area, and an aerodynamic resistance depending on wind speed and the irregularity of the surface. The aerodynamic resistance is about the same size as the resistance for a single leaf, but the crop's surface resistance is usually much smaller than the corresponding stomatal resistance of a leaf. Until a barley

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crop reached a leaf area index (L) of 6, the leaves appeared to act independently, i.e., behaved as L resistances in parallel, each of 1·5 sec cm^{-1}, so that at $L = 6$ the effective surface resistance of the crop was 0·25 sec cm^{-1}. As L increased from 6 to 10 the surface resistance remained almost constant, probably because the lowest leaves were too deep in shadow to keep stomata fully open. So—and this behaviour is typical of well-watered crops in temperate summer weather—the aerodynamic resistance and the surface resistance are about the same size, near 0·3 sec cm^{-1}, and in this state the mean surface temperature during daylight is close to mean air temperature, the exchange of sensible heat with the atmosphere is negligible (i.e., the Bowen ratio is near zero) and the fraction of net radiation used to evaporate water is close to unity.

In assimilation the flux of carbon dioxide encounters first the same aerodynamic resistance, then a similar stomatal resistance (differing quantitatively for the reason given above), but, in contrast with the water vapour flux, has two more resistances in its path to the chloroplasts. At present they are distinguished as a "mesophyll" resistance to the diffusion of carbon dioxide in solution, and a "photochemical" resistance which depends on the intensity of incident light. Calculations for several crops indicate that the mesophyll resistance is between 5 and 15 sec cm^{-1}, and the photochemical resistance in bright sunshine is about 1 sec cm^{-1}.

These concepts are used in a simple model (1.10) that converts laboratory measurements of photosynthesis by single leaves into estimates of rates for a complete crop canopy in the field. An account of a direct test is well advanced, based on results from a field of barley during 1963. Rates of carbon dioxide uptake were estimated aerodynamically in the field, and corresponding rates for single leaves were measured in the laboratory. In weekly totals the predicted growth rates given by the model are close to the measured increases in dry matter obtained by sampling the crop.

Carbon dioxide from the soil. On Great Field II the flux from bare soil was near 1 g m^{-2} day^{-1} in winter and 6 g m^{-2} day^{-1} in summer: from a cropped soil in summer the flux was often 8–10 g m^{-2} day^{-1} (1.11). Although this could supply about one-fifth of the net amount of carbon assimilated by the crop, calculations show that the benefit must be slight. The rate of photosynthesis is determined by light intensity, and atmospheric turbulence is usually vigorous enough to maintain the daytime concentration of carbon dioxide in the crop canopy within 10 or 20 ppm of the free air value (*c* 300 ppm). Any change in the flux from the soil is met by an almost equal and opposite change in the flux from the atmosphere: the total changes little. (Armstrong, Monteith and Szeicz)

Radiometry. A miniature tube solarimeter was designed for use in grass and similar crops of small height (1.13). It is 35 cm long, 0·8 cm diameter and its output is near 12 mV per cal per cm^2 per minute. (Szeicz)

Micro-meteorology—irrigation experiment. The plots were too small to justify any attempt at measuring temperature and humidity profiles over them, and measurements were restricted to the profiles within the canopies.

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Grass. Before the first irrigation, differences were small. After, within 24 hours, the relative humidity at 6 cm above the soil (crop 35 cm high) was persistently *c* 5% greater in the irrigated crop, and the air temperature was slightly *greater* too. Eleven days after the second irrigation, differences of 8% in relative humidity, in the same sense, were measured, but most of this—if not all—is an effect of the more dense and taller crop produced by irrigation.

Potatoes. Three days after irrigation of a crop 90 cm high (from furrow bottom) measurements were made at 30 cm. The relative humidities were 10–20% greater, and the temperatures 1–4° C less in the irrigated crop. Wet-bulb temperature was about the same for both. (Long and French)

Wetness recorder. A new instrument was developed to measure the surface wetness of leaves, and it may also give an indication of leaf turgidity. Possibilities still have to be explored, but two inferences seem certain. Dew forms on grass as discrete drops, but the drops may coalesce—near sunrise—to form a continuous film. Dew on potatoes forms as a continuous film, and the recorder indicates that there is always some sort of good electrically conducting layer on the surface of healthy potato leaves and the dew adds to this priming layer.

Neutron moisture meter. Some improvement is possible in an already very satisfactory instrument and a new model is being designed. (Long)

Irrigation 1964

Woburn. The *lucerne* on at least one of the four plots in the lowest-lying block had suffered severely from winter water-logging. The whole block was ploughed up at the end of May. Almost half of the total yield was obtained at the first cutting (9 June) with no response to the ½ in. of irrigation applied up to that date. At the first *clover* cut (11 June) the inch of irrigation in May produced about 10% increase in yield (near 30 cwt/acre): in the dry weather after June the further yields were 20 (no irrigation) and 36 cwt/acre (3 in. irrigation). As expected after a wet June, the *barley* did not respond to irrigation in May and July. The response of the *sugar beet* to full watering was almost equalled on plots that had 2 in. of irrigation in August and none earlier. (Penman and Barnes)

TABLE 1

Woburn Irrigation, 1964

Crop	Period	Rain (in.)	Irrigation (in.)	Plot	Yield (cwt/acre)	
Lucerne	28 April–28 Sept.	8·0	—	O	76	Dry matter 4 cuts
		8·0	3·0	C	83	
Clover	28 April–28 Sept.	8·0	—	O	49	Dry matter 3 cuts
		8·0	4·0	C	70	
Barley	28 April–17 Aug.	6·7	—	O	34	Grain
		6·7	2·0	C	35	
Sugar Beet	28 April–28 Sept.	8·0	—	O	53	Sugar
		8·0	3·5	C	73	

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Rothamsted. Unavoidable engineering difficulties prevented full use of the equipment when it was needed: doubtless bigger responses would have been obtained had more water been applied. Two somewhat complex experiments were laid out on areas *c.* 400 × 200 ft. For potatoes, there were two varieties (Majestic and King Edward), two seed spacings (12 and 18 in.), two nitrogen levels on a basal PK and half the area was planted with chitted seed. For grass there were two varieties (Meadow Fescue and Timothy) and four levels of nitrogen applied after each cut except the last, on a basal PK. The summary in Table 2 gives responses to irrigation averaged over all management treatments except where these produced an equal or greater effect. (Penman and French)

TABLE 2

Rothamsted Irrigation, 1964

Crop	Period	Rain	Irrigation	Plot	Yield	
Majestic	21 April–21 Sept.	2·8	—	ON_1	13·4	Tons/acre
				ON_2	14·0	
		8·2	2·0	CN_1	16·5	
				CN_2	18·2	
King Edward		8·2	—	ON_1	11·4	Tons/acre
				ON_2	13·3	
		8·2	2·0	CN_1	14·3	
				CN_2	15·7	
Meadow Fescue	21 April–21 Sept.	8·2	—	ON_1	17·1	Dry matter: 2 cuts
				ON_4	41·4	
		8·2	3·0	CN_1	20·5	
				CN_4	49·6	(cwt/acre)
Timothy		8·2	—	ON_1	9·2	Dry matter: 2 cuts
				ON_4	21·5	
		8·2	3·0	CN_1	14·7	
				CN_4	31·9	

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