ROTHAMSTED RESEARCH

Report for 1961

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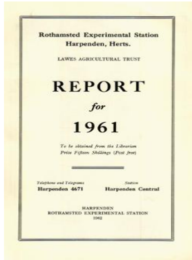

Physics Department

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PHYSICS DEPARTMENT

H. L. PENMAN

D. A. Rose, an Agricultural Research Council Scholar working in the department, was appointed to the staff in January. Dr. K. Yabuki returned to the University of Osaka, Japan, after a year's work on carbon dioxide exchanges between soil, crop and atmosphere, and Dr. G. Contreras returned to Madrid after studying the effect of fertiliser treatment on water-holding capacity of soil (Broadbalk) and crop/weather relationships (six-course experiment). For six months, Dr. P. Gaastra, a plant physiologist from Wageningen, Holland, joined J. L. Monteith for an exchange of ideas on problems of plant growth, a visit made possible by the award of an O.E.E.C. Fellowship. In November Dr. R. Shapiro, from Beltsville, Maryland, came to spend a year working on nutrient release and diffusion in soils, and in December, Mr. C. E. Hounam, Bureau of Meteorology, Australia, arrived for a two-month study of problems and techniques in agricultural meteorology.

SOIL PHYSICS

Soil aeration

A good soil provides firm anchorage for plant roots without undue constraint on their growth as they acquire food, water and air. The pore-space is determined by the nature of the soil particles, by the way in which the particles are assembled in aggregates and by the way in which the aggregates are packed together, and normally it is occupied partly by water and partly by air. For adequate air supply and adequate water supply a compromise is required between the extremes of maximum water content and maximum air content, and although " adequate water supply " can now be specified with some confidence, " adequate air supply " is, quantitatively, a much vaguer concept. Qualitatively, the problem is clear. During healthy growth plant roots absorb oxygen and evolve carbon dioxide, so altering the composition of the air in the soil, and unless the oxygen is replaced and the carbon dioxide is removed the concentration of either gas may reach a value at which plant growth is inhibited and the soil becomes essentially anaerobic. If there is continuity of air-filled pore-space between the root environment and the free atmosphere, then both gases will interchange between soil and atmosphere by molecular diffusion, a process conveniently termed " aeration ". Our quantitative study of the physics of aeration therefore started from study of molecular diffusion in porous systems and how it is affected by particle properties, by aggregate properties and by variable water content.

If the coefficient of diffusion of a gas in free air is D_0, then in a porous solid it will be decreased to an effective value D such that $0 \lessapprox D/D_0 \lessapprox \varepsilon$, where ε is the fraction of pore-space that is air-filled. For loose dry particles the value of D/D_0 is determined partly by ε

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and partly by the shapes of the pores, and as these depend to some extent on the geometry of the particles, D/D_0 can be expressed in terms of ε and a particle-shape factor (k or m). In a dry aggregated material such as soil the particle-shape factor has much less significance, but values of k or m deduced from diffusion experiments can be interpreted as soil complexity factors; in fact, they are structural indices. When there is water in the system it tends to produce some uniformity of pore shape, and its effect on D/D_0 depends very much on the distribution of the water between the small pores in the crumbs and the large pores separating the crumbs. If the crumbs are " solid ", as they are in sand, or, in effect, in a soil whose aggregates are completely waterlogged, then D/D_0 varies as the fourth power of the remaining air-filled pore space, a relationship that implies a rapid increase in D/D_0 in the final stages of removal of water from the inter-crumb pore-space. Further drying takes water out of the crumbs themselves, but the increase in D/D_0 per unit increase in total air-filled pore-space is now relatively very much smaller, and crumb porosity does not contribute much to bulk aeration of the soil, though it does contribute nearly all of the water-holding capacity of the soil. This broad summary of the implications of the first results of the work on diffusion leads to a general specification of a well-tilled soil as one that allows adequate diffusion down the profile between the crumbs and yet leaves the crumbs with adequate pore space to contain and retain water at field capacity.

With the basic physical relationships established, the next phase was mathematical. Given values for the oxygen requirement of a soil (that is of roots and of soil organisms), the distribution of gas composition with depth in the profile can be calculated for various assumed forms of pore-space distribution. An important result emerged. Unless the value for oxygen requirement is absurdly high, or the packing is such that D/D_0 is absurdly low, it is impossible to predict gas concentrations in the inter-crumb pore-space which are likely to limit plant growth even in soils where poor aeration is suspected. The mathematical analysis was then pressed further, recognising that the composition of the soil air does not necessarily represent the condition at the root surface, because the diffusion path has to be completed through a film of water on the root hair. The rate of diffusion of oxygen in water is only about 10^{-4} times its value in air, and, as a further complication, oxygen is so much less soluble than carbon dioxide that the relative concentrations of the two gases in solution may be the reverse of those in air with which the solution is in equilibrium. Except during the day or two needed to bring the soil to field capacity after rain, the aeration problem lies in what happens between the outside and inside of a crumb.

As a help towards understanding, and a guide towards experiment, a crumb can be idealised as a sphere with respiratory activity uniformly distributed throughout its volume. For such a system, in equilibrium with its environment, the concentration of a diffusing gas at a distance r from the centre is

$$\delta_r = \delta_a + S_c\,(a^2-r^2)/6D_c \qquad (1)$$

where δ_a is the concentration at the surface, a is the radius of the sphere, S_c is the respiratory activity per unit volume of sphere and

D_c is the coefficient of diffusion of the gas through the pores. As the size of the sphere increases, the oxygen deficit increases; and for a given size the same effect is produced by decrease in D_c, which may happen for several reasons. Furthermore, as crumbs become wetter, gaseous continuity is decreased and ultimately diffusion is restricted to movement through the water. Under such circumstances the oxygen deficit may be large enough for the centre of the crumb to be effectively anaerobic. For further analysis we can measure or calculate values of δ_a, a and S_c with adequate accuracy: the real problem is to get an estimate of D_c. Some progress has been made in the analysis (1.4) concluding ". . . whereas it is clearly impossible to calculate a universally acceptable 'optimum crumb size', it seems possible to estimate the crumb size for a given soil that would preclude the onset of anaerobic conditions in the range between wilting point and field capacity most prevalent during the season of active crop growth".

Direct measurement of diffusion within the micro-structure of a crumb is difficult, but some measurements have been made with sufficient precision to test alternative theoretical analyses. Large synthetic crumbs are made by powdering dry soil, packing it into a cylindrical mould, wetting it and allowing it to dry into a coherent mass. Using the standard hydrogen technique, a value of D_c is measured. As a supplement, an indirect estimate is then made. The dry block is crushed and the 1–2-mm. fraction sieved out and repacked in the container. A diffusion measurement is made on this material, to give a value of D_r, say, and is then repeated after the crumbs have been saturated with paraffin (kerosene) and drained under tension until all the inter-crumb pores are air filled and the crumbs themselves remain just fully saturated, the second operation giving a value D_v, say. (The use of paraffin instead of water avoids swelling complications.) The difference D_r–D_v is a measure of the contribution of the crumbs to the total diffusion, but it is not a unique measure of diffusion in the crumbs, because it shows some dependence on the way the crumbs are packed, and on the shape of the crumbs.

Of the two theoretical expressions available the simpler is

$$D_c/D_0 = (D_r - D_v)/(D_0 - D_v) \quad . \quad . \quad . \quad (2)$$

and over the range of soils studied it over-estimates the value of D_c/D_0. This particular equation comes from the treatment that led to the particle-shape parameter k. The second, more complex, equation comes from the treatment that led to the particle shape factor m, and it underestimates the value of D_c/D_0. But both expressions for D_c/D_0 put a given series of soils in the same order. Using the indirect method on natural soils, it is clear that the micro-structures of crumbs vary in their ability to transmit gases by diffusion, and it is useful to introduce crumb complexity factors k_c and m_c (analogous to the bulk soil factors k and m) to express this variation quantitatively. The values are

$$k_c = \{\varepsilon_c/(1 - \varepsilon_c)\}\{(D_0/D_c) - 1\} \quad . \quad . \quad . \quad . \quad (3)$$

$$m_c = \log (D_c/D_0)/\log \varepsilon_c \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where ε_c is the porosity of the crumb.

The technique was applied to crumbs from four of the Broadbalk plots, and Table 1 gives values derived from the simpler expression for D_c/D_0 (eq. 2).

TABLE 1

Complexity factor for crumb micro-structure (*Broadbalk*)

Plot	Treatment	Crumb Porosity (ϵ_c)	D_c/D_0 (eq. 2)	k_c (eq. 3)
3	No fertiliser	0·222	0·036	7·6
2	FYM	0·274	0·063	5·6
8	Sulphate of ammonia + minerals	0·264	0·061	5·6
16	Nitrate of soda + minerals	0·267	0·057	6·1

The soil on the unmanured plot has failed to attain (or maintain) the same crumb porosity as the other three plots, and it has a greater crumb complexity. The uniformity of the other three plots suggests that it is the activity of plant growth (all produce big yields) that is correlated with these particular measures of crumb structure, and that the dung has had no extra effect on either crumb porosity or complexity.

Table 1 is for dry crumbs, and the next stage of the work will be an attempt to make similar measurements on crumbs wetted over the range experienced by soils in the field.

Soil structure

Spring beans were again grown in the second test year after ploughing out former ley and fallow plots. Half of each plot was deliberately cultivated at the wrong time to degrade the known better structure of the former ley plots, and to worsen further the poorer structure of the former fallow plots. A satisfactory level of bad farming was achieved by disc harrowing the soil when it was very wet.

Plant population and plant height were lower on the mismanaged half plots, and yields were about 20% less. The contrast was about the same between former ley and former fallow plots, i.e., in a self-evident shorthand, ley + good cultivation > ley + bad cultivation = fallow + good cultivation > fallow + bad cultivation. (Currie.)

Soil water

Measurement of the movement of water vapour in soils continued, and results are now being prepared for publication. Leaving a summary until a later report, a minor by-product is worth notice. Subsidiary experiments on the effect of salt in the soil water suggest that placed fertiliser will not be a serious competitor with seeds in their need for soil water (1.10).

Some incomplete measurements of the " available " water in the profiles of Broadbalk plots 2A, 3 and 8, based on the pF meter of Monteith and Owen, agree very well with those of Balcerek and Russell in 1945 obtained by a completely different technique. In the top few inches the available water of the FYM plot (2) is about 40% greater than that of the unmanured plot (3). Below about 15 inches the difference is the other way round, but the information is not complete for the whole depth that might be explored by plant roots. (Rose and Contreras.)

Soil water

The neutron-scattering technique for estimating soil water content is at last in the form we wanted. The delay has not been unrewarding, for the unit is better than it could have been even a year ago, and within the volume of a portable radio set the unit has a self-contained power supply, a five-decade counter, a rate meter and weighs only 14 lb. (Long.)

Electrical charges on clays

In the preparation of material to study the effects of different cations on the behaviour of clays, the early stages aim at producing a homo-ionic clay free from exchangeable aluminium. In the course of the experiments the aluminium inevitably reappears, and as it must come from the clay, it is presumed that there is degradation of the edges of the crystallites, a result of the strain produced by an electrical potential difference between the edges (positive) and the planar faces (negative). Reasoning indicates that the aluminium in the detritus—detectable as exchangeable aluminium—should be equivalent to the known positive edge charge of the clay in acid solution (1.3). An extensive series of proving experiments has produced conflicting results. The qualitative behaviour is as predicted: some of the quantitative results are as expected, but not all, for there seems to be too much aluminium coming out of the lattice. It may be that we are detecting a phenomenon suspected some years ago by Greene-Kelly—that the hydrogen ions in the wash water may release aluminium from the clay lattice. If so, then these special conditions of a laboratory experiment may be relevant to the field conditions that produce " weathering " of clays. (Cashen.)

Agricultural Meteorology

Micro-meteorology

The measurement of temperature, humidity and wind profiles over grass continued until the end of the summer, so completing three years' observations. Re-calibration of the soil thermometers, buried for three years, showed no change greater than 0·1° C.

Two sets of equipment were run close together in a crop of beans on the western half of the same field. The first was our standard equipment. The second was a system of aspirated wet- and dry-bulb units which had to be specially built for the purpose, and involved some trouble in finding a suitable pump for the aspiration. Although aspiration gets over the difficulty of having to use a variable psychrometer constant (not that it has ever embarrassed us, though others have challenged our practice), it has brought in new troubles of its own, particularly at low wind speed, where there is some evidence that it disturbs the natural air flow. Analysis of the records is, however, far from complete.

A set of fifty-two bi-directional vanes, mounted in four tiers on

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a large wind vane (about 12 feet long, 4 feet high), was built to get some idea of the nature of the turbulence in the air over a crop, partly for its own meteorological interest in adding to understanding of heat, vapour and carbon dioxide transfers, and partly to get some knowledge of the first (or last) stages of the movement of insects or spores from (or to) a crop. Records, taken with a ciné camera, look good, but no analysis has yet been attempted. (Long.)

Radiation balance

As a complement to previous work on radiation components, the diurnal variation of effective surface radiative temperature was measured on cloudless days, over a variety of surfaces. (Once again, we are grateful to Professor P. A. Sheppard for the loan of a Linke–Feussner radiometer for this work.) Loose bare soil showed the greatest diurnal range, a maximum of 44° C. being estimated on a day when the maximum air temperature reached 25° C., and water surfaces experienced least diurnal variation. Several kinds of vegetation, other than short grass, behaved much alike, and the inter-relationship of surface temperature and net radiation was consistent with a theoretical model of heat and vapour transfer from leaves to atmosphere.

Analysis of our own solar-radiation records, and of those from Meteorological Office stations, produced a way of estimating mean solar-radiation intensity in the presence of cloud and atmospheric pollution. Combination of this with previous work on long-wave radiation now makes it possible to estimate the seasonal variation of net radiation for natural surfaces almost anywhere in the British Isles. "Net radiation" is the dominant term in estimates of potential evaporation, as made here and elsewhere, and this new work should remove some of the hitherto unavoidable crudities of our present method of estimating evaporation from weather data. First computations suggest that there is little difference in evaporation between south England and north Scotland; and that the evaporation rate from a standard M.O. tank is almost independent of wind speed and humidity—the tank is, effectively, a net radiometer.

Water balance

A second transpiration gauge, built by the Cambridge University Engineering Laboratory, was installed in March on the same section of Great Field, about 200 yards west of the first balance. The crop on the second site was spring beans: the first site continued under grass (grown for hay) and although the ratio of transpiration from grass and from beans varied from week to week, the totals from 29 April to 3 September were not very different: 10·7 inches for grass, 9·9 inches for beans, while the totals for two open water evaporimeters nearby were 14·3 inches for a standard M.O. tank and 16·0 inches for a U.S.D.A. Class A pan. (In the same period the estimated total potential transpiration at Woburn was 12·1 inches.) For three weeks at the beginning of May transpiration from the grass was 50% greater than from the M.O. tank, but from June onward transpiration from both grass and beans was consistently less than the open water evaporation, indicating a shortage of soil water.

Further study of the energetics of condensation has led to the concept of " potential condensation " as the maximum possible rate of dew formation. Calculated values agree well with observations in various parts of the world (1.5).

Carbon dioxide balance

The six-point gas analyser was used throughout the summer to measure the vertical distribution of concentration in and above grass and beans, horizontal variations downwind from the edge of a crop and absolute concentrations over different crops at the same time. The carbon dioxide flux from the soil was measured gravimetrically by absorption in soda lime, and volumetrically by absorption in baryta, and the latter technique was adapted for electrical recording. As orders of magnitude, the winter flux was 0·1 mg./cm.^{2}/day (= 10 lb./acre/day) and the summer flux beneath a crop was 1·0 mg./cm.^{2}/day, a major contribution to crop assimilation (2–3 mg./cm.^{2}/day). To assist interpretation, laboratory measurements of rates of photosynthesis and respiration were made on single leaves at controlled levels of CO_2 concentration, light intensity, temperature and humidity.

Radiometry

A miniature net radiometer (diameter 4 cm.) was made for the Hannah Dairy Research Institute for measuring the radiation balance of grazing sheep, and a similar instrument was sent to Dr. G. Stanhill, National and University Institute of Agriculture, Israel, who is using several Rothamsted devices in his crop-water studies, a consequence of Monteith's visit to Israel in 1959 (1.2). Another radiometer, and some of Long's micro-meteorological equipment were lent to the British Schools' Exploring Society expedition to Central Iceland in 1960, and their recent report indicates that performance was good. Israel and Iceland provide a fair climatic range for proving trials of our equipment.

Nearer home, equipment for integrating solar radiation and net radiation was installed at Woburn (described in 1.6). A new design, modified to satisfy a new need, will measure energy in the photosynthetic wavelength range, 0·4–0·7 μ, and is now being tested. (Monteith, Szeicz, Yabuki, Gaastra.)

Woburn irrigation experiment, 1961

Except for one wet week in June, and another in July, this was a dry summer up to the beginning of August. The equipment was in use from mid-May until August, and all crops responded to irrigation. *Grass*: For a second-year crop, growth was rather poor, and after diagnosis of impeded drainage it was decided to plough up the plots in September, and to subsoil afterwards. Without irrigation, there was no important response to nitrogen, or potassium, or both. There was a big response to irrigation under all fertiliser treatments, but within the watered treatments three gave almost the same yield, with the fourth (high N, high K) outstanding.

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Laboratory work has started to find out why this Woburn soil can supply enough potassium to produce about 4 tons/acre, but needs a supplement to get the yield up to 5 tons/acre of dry matter. *Spring beans*: The end of 1960 was too wet for husbandry, and the crop intended—winter beans—could not be drilled. The response to irrigation was better than any previously obtained (1957–59). *Barley*: The response to water was about the same as to extra nitrogen: it is usually smaller. *Early potatoes*: The yields in the table are for plots given normal cultivations. Six of the twelve had minimum cultivation and a simazine spray to try to control weeds. It was not very successful, and yields suffered, the average of the unwatered plots being 4·8 tons/acre and of the irrigated plots, 8·8 tons/acre. (Penman and Barnes.)

TABLE 2

Woburn Irrigation, 1961

Crop	Period	Rain (inches)	Irrigation (inches)	Plot		Yield
Grass	1 May–11 Sept.	6·6	—	O	45	Dry matter, cwt./acre. 6 cuts
		6·6	6·0	C except CKN_4	70	
					98	
Spring beans	1 May–21 Aug.	5·4	—	O	14	Grain, cwt./acre
		5·4	4·5	C	32	
Barley	1 May–31 July	3·6	—	ON_1	24	Grain, cwt./acre
				ON_2	32	
		3·6	3·2	CN_1	30	
				CN_2	37	
Early potatoes	1 May–10 July	2·5	—	ON_1	5·9	Tubers, tons/acre
				ON_2	6·9	
		2·5	4·0	CN_1	13·3	
				CN_2	15·0	