ROTHAMSTED RESEARCH

Rothamsted Report for 1966

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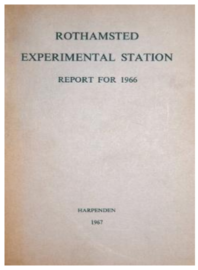

Physics Department

H. L. Penman

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PHYSICS DEPARTMENT

H. L. PENMAN

Miss J. A. J. Walker retired after 37 years of devoted service to the department. J. A. Currie took part in a symposium on soil management, in Brno, under the auspices of the Czechoslovak Ministry of Agriculture, J. L. Monteith visited Israel and Nigeria for symposia on radiation and on water use by crops, H. L. Penman attended the second meeting of the Co-ordinating Council for the International Hydrological Decade, in Paris, and, with D. A. Rose, took part in the UNESCO symposium on soil water, in Wageningen.

Mr. W. Stiles returned to the Grassland Research Institute, and Mr. F. J. Wangati to the East African Agricultural and Forestry Research Organisation. For most of the year Dr. T. A. Bull (David North Plant Research Centre, Queensland) was working on leaf-growth problems, and for shorter periods Mr. A. Thom (Edinburgh University) and Mr. C. A. Igeleki (Nigerian Meterological Service) were helping with research problems or studying the application of results to technical problems. Mr. H. Rowse came from the School of Agriculture, Sutton Bonington, for three years' post-graduate study.

D. A. Rose was awarded a Queen Elizabeth Fellowship, and will work in Australia from 1967 to 1969.

Introduction. Water is one of the main requirements for plant growth. A question answered about 20 years ago was, "How much water is used?", and in 1954 a technical bulletin on the calculation of irrigation need was produced by a working party drawn from several research organisations. This has been continuously useful, and it has been reprinted several times, but with better and more extensive recent weather records available a new edition is imminent, prepared by Mr. L. P. Smith of the Meteorological Office. Our recent experience on radiation exchanges suggested minor modifications in some of the empirical equations used in calculating potential evaporation: some of the new estimates, mainly away from south-east England, will be about 5% greater than the old ones.

A second question—"How much of what is used is needed?"—was, and is being answered in the irrigation experiments, started at Woburn in 1951, and at Rothamsted in 1964. Broadly, the first 12 years' results from Woburn showed that the meteorological estimate of need, based on the behaviour of a hypothetical crop, is a good index to average farming benefit when the need is satisfied: within the past two years the policy for the Woburn experiment has moved to study of interactions of irrigation and management or pest and disease control. At Rothamsted two-thirds of the irrigation experiment remains more conventional (varied amounts of water), but management and plant variety are included as experimental variables where possible. Unfortunately in both the first two full years of the experiment (1965 and 1966) the need for irrigation was slight, and

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subsequent rain rendered applications superfluous. This is an occupational hazard, we know the odds, and, perforce, accept them, but unwelcome accidents in soil management, for the second year, produced very irregular plant covers on the "macro-plots"—the third part of the irrigation experiment. Here, on two plots *c.* 100 × 100 m, we concentrated all our weather equipment to get detailed records of energy, water and carbon dioxide balances, with intensive relevant botanical measurements (leaf area, stomatal resistance, photosynthesis and respiration rates, etc.). Choice of representative sites on the plots was almost impossible: they must be near the middle to ensure a barely adequate fetch and here, at a census on 6 May when the bean plants were 5 cm tall, random counts showed from 0 to 36 plants per metre length of row. Later there were very big differences in plant height and development across the field, a most undesirable condition for good micrometeorology or adequate growth analysis.

The first year's work on the large plots (1964: Timothy and Meadow Fescue) was also the first occasion for intensive use of the neutron moisture meter (1.8). As noted then (*Rothamsted Report* for 1964, p. 38), there were two surprises. First, the apparent evaporation from the irrigated plots was much greater than predicted, and second, the grass responded much less to irrigation than expected from Woburn experience. Closer examination of the records, still in progress, shows that not all the water leaving the spray-lines reached or stayed in the upper soil profile, and with corrected water balances the first discrepancy becomes acceptably small. More important, it is clear that irrigation of our clay soil does *not* bring the top layer to field capacity: because of cracks and fissures the water penetrates the soil, sometimes to a metre depth (the limit of measurement in 1964), and although this need not affect availability for transpiration, it may be disadvantageous for nutrient uptake by the roots. Large amounts of irrigation at long intervals may not be best practice on shrinkable clay soils, even though their reserve of available water is great.

Soil physics

Clays. Work on anomalous flow in colloidal systems is summarised in Abstracts of Papers (1.5; 1.6). The effects depend on changes in the particle arrangement during shear, and inferences about the nature of these changes is being tested by experiment.

Cation exchange is important in the deflocculation of clays. As the edge faces of clay crystals can absorb anions, their contribution to deflocculation was measured. It seems to be negligibly small. (Cashen)

Aeration. We assumed responsibility for operating the soil respirometers at the National Institute of Agricultural Engineering, 15 miles away at Wrest Park, Silsoe. Considerable reconstruction was needed, and in spite of unforeseen snags, some useful work was done by a single operator limited to short daily visits when previously there was a team able to work night and day when needed at critical periods. In the saga of engineering difficulties only one history will be noted. Each of six tanks needed 2 tons of soil, and the search for a real soil was solved by the Hertfordshire

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County Surveyor, who kindly gave us all we needed, "in the interests of science", from a road-widening scheme on the edge of our farm. Twelve inches of sand were placed in the bottom of each tank to lie below the eventual water table, then the Rothamsted soil, after going through a soil shredder (taking out most of the less-desirable flints), was put on top. Eventually, after killing most of the ants in three of the tanks, the tops were sealed while the respiration rate of the uncropped soil was measured. This complete, the seals were removed and 6-in.-tall kale plants transplanted. When these were established the seal was restored with the plants as the only path between the soil and the outside atmosphere. All measurements this year were based on a maintained mean oxygen concentration of 21% in the air beneath the lid and above the soil. The concentration of carbon dioxide sometimes rose to about 4%. Results are necessarily very provisional, but one confirms previous experience at Wrest Park: Rothamsted topsoil consumes oxygen at about 8 l/m² per day (August). Later (September) the combined uptake by kale and organisms was less, partly because the soil was then cooler and partly because the soil packed more closely as it settled.

Measurement of the effect of atmospheric turbulence on gas exchange at the soil surface showed no effect in columns of uniform structure (to 1 m, real; to 10 m, simulated), but where there is a partly impervious crust there is an apparent increase in the rate of diffusion at the surface. The phenomenon may affect the efficiency of a mulch as an evaporation suppressant. A first attempt to measure it failed for technical reasons, and another attempt will be made.

Work at Wrest Park limited time for diffusion studies in crumbs—and encouraged successful simplification and automation of the technique. Application of previous work was presented at an international symposium (1.7). (Currie)

Soil water. When water evaporates into a constant environment (humidity and temperature) from a deep uniform bare soil initially at field capacity the variation of water content, θ, with depth, z, and time, t, is such that θ is invariant with $zt^{-\frac{1}{2}}$. From the profiles the diffusivity can be calculated as a function of moisture content (1.12). F. J. Wangati (1.1) obtained the same result from a larger volume of soil in a less closely controlled room environment, and derived values of diffusivity of the same order.

The converse problem has always been a severe technical challenge, much easier to solve on paper than by experiment. Attempts to get controlled water uptake by dry soils from a liquid source failed on real soils. Swelling on wetting caused breakdown of structure, and after many failures the attempt was abandoned. Good and reproducible results were obtained for inert materials—sepiolite and ignited soils—giving wetting profiles invariant with $zt^{-\frac{1}{2}}$, and calculated values of diffusivity a little bigger than the drying diffusivities at the same water content. On these selected materials a wide range of experiments was done to study the effects of environment and previous management. The range of soil wetness was usually small, from air-dry up to pF 4·2, but this encompasses

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the range in which the relative importance of movement as liquid and as vapour is a source of controversy in arid-zone agricultural hydrology. Two parameters were studied. The first—diffusivity—is a property of the soil and its water content, but not of the boundary conditions applied. The second—sorptivity—does depend on the boundary conditions, and the concept probably needs some redefinition. As it is, it is a measure of the amount of water sorbable by a dry soil, and, as a number, is obtained from $S = Qt^{-\frac{1}{2}}$, where Q is the total amount taken up in time t from an atmosphere at constant relative humidity. The effect of temperature on diffusivity is predictable for wholly vapour flow or wholly liquid flow, and measured values fall within the two limits, permitting a rough assessment of the relative contributions to transport. These assessments were confirmed when the sepiolite or ignited soil had salt added. Even after ignition, soils with a long record of treatment with FYM differ in both qualities from neighbouring unmanured soil. Aggregate size has some effect on sorptivity, and where in the 1–2 mm range Woburn soil has a maximum of S, Rothamsted soil has a minimum, probably an effect of the very different mean particle size in the sand and clay respectively. As expected because of the changed boundary conditions, the sorptivity is decreased in still air, or when the soil is mulched; addition of an evaporation suppressant has the same effect. (Rose)

The neutron moisture meter is now well through its important proving trials (1.8). Our original model was given to the Chemistry Department, and two new ones were built, one as a spare for emergency during the busy summer period. During the summer moisture profiles were measured on about 25 days between the end of May and the middle of September: (*a*) on the macro-plots under beans at three points on the irrigated plot and one in the transpiration gauge, at four points on the non-irrigated plot and one in its transpiration gauge; (*b*) at two points on each of the irrigated and non-irrigated plots of potatoes. Superficially there seems to be no major clash in the evidence of the samplings in comparison with the calculated potential transpiration: both the measured water content integrated over the depth of the gauge and the total weight of the transpiration gauge show that the gauge received much less water than the nominal amount of irrigation supplied to the plot. Though these two quantities do not agree with each other, one inference from both is that the irrigated beans transpired faster than those not irrigated. Much of this difference must be attributed to the uneven stand: on the irrigated plot and its transpiration gauge germination was fairly good, and on the gauge the plant had to be thinned to the same leaf-area index as the surround; on the non-irrigated plot hardly any plants germinated on or near the gauge, gaps had to be filled by transplanting, and these transplants always grew slower than plants elsewhere. Measured differences between transpiration rates, already clear before the first irrigation, may have been augmented by the irrigation, but this is not the best way to test hypotheses on the meteorology of transpiration. In this wet summer neither beans nor potatoes took significant amounts of water from below 80 cm. (Long, French and Szeicz)

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Agricultural meteorology

Micro-meteorology. All the equipment was on the macro-plots, with an addition. An old recorder was rebuilt and used with sensors at constant height across the non-irrigated plots (6 points). Temperature, humidity and air flow varied greatly across the site, but with the very uneven crop cover this is not surprising. The large differences in crop height and population, within and between plots, probably nullify the observed contrasts in humidity and temperature gradients, leaf temperature and leaf wetness. As in the barley in 1965, ventilation was different at the middle of the two plots, depending on wind direction. (Long and French)

Planned measurements of carbon dioxide profiles over both plots were abandoned because of the uneven crop cover and frequency of rain. Instead, the equipment was used on one plot to measure carbon dioxide concentrations at six heights within the crop and six heights above it. At the same time an infra-red gas analyser for water vapour was used to measure humidity profiles, an exercise made possible by the kindness of Hilger–I.R.D. Ltd. in lending us the equipment for extended trial. There are instrumental stability problems yet to be solved.

Solarimeters installed in the beans gave vertical gradients of total and infra-red radiation, profiles of net radiation were measured on several days and throughout the summer net radiation above the crop and heat flux in the soil beneath it were recorded continuously. (Monteith and Szeicz)

Water relations. The diffusion porometer (*Rothamsted Report* for 1965, p. 31) was used regularly on the bean crop. Stomatal resistance often decreased slightly during the morning, and increased, more rapidly, in the late afternoon. When the crop was 1 m tall (early July), the resistance of leaves in the top 50 cm of the canopy differed little, whatever their age, but late in July resistances began to increase, probably because of senescence. Stomatal resistance and leaf-water potential seemed to be uncorrelated; the potential measurements varied greatly from leaf to leaf, but in the mean tended to a constant value over about 40 cm of the stem. (Bull, Stiles and Wangati)

Growth analysis. The amount of dry matter, and the distribution of leaf area with height, were measured weekly. The total leaf area of 10 plants was measured every weekday, and the rate of leaf expansion was more closely correlated with maximum air temperature than with any other weather parameter. The rate was near 5% per day at 10° C, and near 10% per day at 20° C, until mid-June, when relative growth rate decreased, and the correlation ceased, probably because flowers and pods developed (1.4). (Bull).

Laboratory measurements on beans. Development of apparatus and its use went on together. At regular intervals whole plants were cut off close to their bases, brought to the laboratory and chosen leaves placed

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inside leaf chambers with the plant stems in a suitable water supply. Dark respiration rates were measured and then rates of photosynthesis at varied light intensities and constant carbon dioxide concentration (300 ppm), or at varied carbon dioxide concentrations (0–2,000 ppm) and constant light intensity. Leaves of various age were used, and, in all, more than 100 response curves were obtained. Respiration and photosynthesis rates, and their temperature coefficients, were measured on stems and pods too. Analysis of the results is being greatly helped by the computer. (Parkinson)

Surface exchange coefficients. Within a crop, as above, exchange rates of important qualities depend on transfer coefficients affected by turbulent mixing in the air, and by leaf size and orientation. To get realistic coefficients for a bean leaf, a replica in aluminium was studied in the wind tunnel of the Plant Pathology Department. Frictional air drag was measured by a moment balance; heat transfer was measured by electrical heating; evaporation (water and organic liquids) was measured when the "leaf" was covered with filter-paper and saturated. Only one result need be noted. The skin friction coefficient decreases as wind speed increases; in the open the aerodynamic roughness of many field crops seems to decrease as the wind speed above the crop increases.

Other parts of this work have been done, and the remainder will be done, in the University of Edinburgh. It is a pleasure to acknowledge the help given, and promised, by Dr. M. A. Ross (wind-tunnel facilities) and the co-operation of the Department of Meteorology. (Thom)

Porometer calibration. Two independent methods gave concordant results differing in important respects from those of Dr. C. H. M. van Bavel (whose idea was copied). The time taken to reach a given relative humidity is proportional to the square of the length of path, confirming a theoretical prediction, but not van Bavel's experimental result. (Basically, this is $zt^{-\frac{1}{2}}$ = constant, appearing again: see "Soil water", above.) At uniform temperature the temperature coefficient is small, but the device is very sensitive to temperature differences. In the field leaves with partly or wholly closed stomata will often be several degrees warmer than the air in bright sunshine, and unless the excess is taken into account, important errors are likely. (Bull and Monteith)

Water potential. For many years the modified Spanner technique (*Rothamsted Report* for 1958, p. 36), with manual reading, has been a great experimental asset. To meet the very much larger demand on it, the equipment was redesigned to handle up to 50 samples automatically. After generally successful experience during the summer, minor imperfections are being made good and a descriptive account prepared. (Monteith, Rowse and Wangati)

Solarimetry. Four sets of solarimeters with integrators were built, two for our own use, and one each for Broom's Barn and Saxmundham. The instrument developed in the department some years ago is now in commercial production. (Szeicz)

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Analysis. Knowing the profiles of temperature, humidity, net radiation and carbon dioxide in a crop canopy, it is possible to calculate the vertical flux of carbon dioxide at all levels, and infer where it is going to or coming from. Computer programmes for this and other kinds of processing were kindly drawn up by the Statistics Department, and we have now got the result of the first analysis. Measuring from the top of the bean crop, the rate of uptake of carbon dioxide was a maximum at about 20 cm, it decreased to zero at about 60 cm and then became negative, i.e. the respiration rate exceeded the assimilation rate. Indirect estimates of transfer coefficients within the field canopy are being attempted from the known wind profile and the wind-tunnel measurements of drag coefficients. These coefficients (as their inverse) give a measure of atmospheric resistance to carbon dioxide uptake; then comes, in series, the stomatal resistance, either to be measured directly (porometer, above) or calculated from laboratory measurements of transpiration rate, and there is now a computer programme for this calculation. There is also resistance in the complex biochemical phases of uptake, and a single model for photosynthesis, now being tried, allows for an enzyme reaction preceding the carboxylation stage, and for the accumulation of soluble carbohydrates in the leaf cells. A programme for the complete chain is now being prepared. (Long, Monteith, Parkinson, Szeicz and Thom)

Irrigation

Periods of need were very brief, and the main one at the beginning of June was followed by three wet weeks.

Rothamsted

Potatoes. Except for irrigation, the main variates were variety (Majestic and King Edward) and spacing (12, 15 and 18 in. apart in rows). One inch of irrigation was applied in mid-July, and there was nearly an inch of rain in each of the 4 weeks after. There was a small positive response, of the order of the standard error, from 17·0–17·4 tons/acre in the mean, with a clear effect of spacing: 12 in., 17·4–18·4, 15 in.; 17·2–17·7, 18 in., 16·4–16·0 tons/acre.

Barley. One inch applied early in June was followed by 2·8 in. of rain in the next 3 weeks. The response was very small, with dry-matter yields of grain of 38 cwt/acre (control), and 39 cwt/acre (irrigated).

Beans. Irrigation on the macro-plots was more liberal, attempting to achieve maximum contrast in the root environment. There were two irrigations early in June (0·4 and 1·0 in.) and one in mid-July (1·0 in.). As noted already, crop establishment was very different on the two plots, and the irrigated plot could be expected to outyield the other for this reason alone. The yields of grain, as dry matter per acre, were: non-irrigated, 19 cwt; irrigated, 23 cwt.

Woburn. There were only two crops, spring wheat and potatoes. For the first 15 years of the experiment Series IV carried a ley of some sort, and

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in the expectation that it would be less contaminated with nematodes than its neighbours, it was used by the Nematology Department for an experiment on nematode control, together with Series I, which last carried potatoes in 1961. The remainder of the site, under wheat, was similarly used by the Botany Department to look at possible interactions of CCC and water supply.

Potatoes. There were 2 in. of irrigation applied at the end of May and the beginning of June, and a further inch in mid-July. For both varieties (Pentland Dell and Maris Piper), and on both series ("with" cysts and "without" cysts), irrigation treatments coincided with decreases in yields of between 2 and 3 tons/acre. On the "without" series the decrease was statistically significant, but on the other it was only a little greater than the standard error (*c.* 1·5 tons/acre). Here the range of individual plot yields was from 3 to 20 tons/acre, a rather large range that needs closer examination.

Wheat. This had the same irrigation as the potatoes, with a minor difference in timing. The combinations of irrigation, spraying and nitrogen treatment (four levels) produced a big range in individual plot yields (15–54 cwt grain/acre) with general means of 33, non-irrigated, and 40 cwt grain/acre, irrigated. Without the CCC spray the response was from 32 up to 40, i.e. spray improved the non-irrigated yield by about 7%, but had no effect on the irrigated crop. (Penman, and many others)

Self-heating of hay

Our share in the work (*Rothamsted Report* for 1965, p. 107) ended. The main phases are clear and, contrary to popular opinion, a wet haystack will not ignite. The chance to ignite comes only when the high temperature is maintained long enough to distil off all the water. When moisture loss was restricted, samples took several weeks to creep from 70° to 100° C; when distillation equalled the original water content temperatures of up to 200° C were attained with a steady rise of 10° C/h. (Currie)

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