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Report for 1962

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ROTHAMSTED
EXPERIMENTAL STATION
REPORT FOR 1962

Physics

Rothamsted Research

Rothamsted Research (1963) *Physics ;* Report For 1962, pp 33 - 39 **- DOI: https://doi.org/10.23637/ERADOC-1-95**

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PHYSICS DEPARTMENT

H. L. PENMAN

After fifty-one years' service W. C. Game retired at the end of September and A. T. Day took over the duties of meteorological observer. W. C. Game returned, to work part-time on mechanical analyses for Chemistry and Pedology Departments. J. L. Monteith was awarded the Buchan prize of the Royal Meteorological Society for notable contributions to the study of micro-meteorology, 1957–61. He presented a paper at the meeting associated with the opening of the Australian phytotron in Canberra, and on the way to Australia he spent a month working with Prof. F. A. Brooks in Davis, California. J. A. Currie was awarded a Kellogg Foundation Fellowship and is now at Cornell University, Ithaca. Doreen Armstrong joined the department in October, to share in the work on radiation and carbon dioxide balance. D. A. Rose was awarded the Ph.D. degree of London University.

For six months, Prof. B. O. Blair, Department of Agronomy, University of Purdue, Indiana, studied agricultural meteorology. Dr. R. Shapiro completed his year in October, working on potassium release from Woburn soil; in September Dr. J. M. dos Santos came as a British Council Scholar to study micro-meteorology.

Soil Physics

Electrical charges on clays. Although some of the harmful effects of soil acidity can be avoided by good field management (e.g., by liming), knowledge of the behaviour of acid soils is far from adequate. When a neutral soil is leached with acid (perhaps from decomposing organic matter) the soil becomes acid, and remains acid when the causative agent is removed by washing. In the first phase the exchangeable cations of the clay are replaced by hydrogen ions to form a hydrogen clay, but hydrogen clays are unstable. It is almost thirty years since Paver and Marshall suggested that the hydrogen ions attack the edges of the clay crystals, so releasing aluminium from the clay lattice, and it is the aluminium ions that become the exchangeable cations held by clays. This suggestion, now accepted and abundantly confirmed by workers in agricultural science, is almost unknown—or ignored—outside soil science: elsewhere "hydrogen" clays are studied as persistent rather than ephemeral.

Attack at the edges, where three hydrogen ions are needed to release one aluminium ion, necessarily implies that in some environments the edges should exhibit positive charges (predicted by Marshall, though he was not successful in one experimental test), and much of the department's work on the physical chemistry of clays has been in the detection and measurement of these edge charges (Schofield, Samson, 1939–54; Cashen 1954 to date). Schofield recognised that the broken edges would expose groups of atoms sensitive to a change in pH of the medium, and devised ways of measuring the contribution of the edges to the total charge of the clay. All

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confirmed that the edges were negatively charged in an alkaline medium, and positively charged in an acid medium.

Schofield and Samson treated kaolin with *N*-KCl at pH 3 and then washed it with water. Initially the high salt concentration repressed the diffuse double layers, allowing the clay particles to pack together (so-called "salt" flocculation), and during the washing the appearance of the suspension changed in a way suggesting that as the neutral salt was removed the repressing effect disappeared, so permitting interaction between positively charged edges and negatively charged planar faces to form a loose "house of cards" structure.

The assumption that the clay was a pure potassium kaolin was not confirmed. Electro osmotic measurements (*Rep. Rothamst. exp. Sta.* for 1958, p. 33) showed that the clays contained much exchangeable aluminium. Close examination of what happens during the washing process (*Rep. Rothamst. exp. Sta.* for 1960, p. 40) suggested that no positive charge was left after washing with water, and that the effective negative charge was equivalent to the K^+ content, which gave rise to the diffuse layer, the rest of the negative charge being balanced by Al^{3+} ions held on the surface in a Stern layer. A plausible explanation for the rapid appearance of aluminium ions in the exchange complex is that, during the washing out of the neutral salt, there is a transient phase in which there are free charges on edges and faces, and the electrical stress thereby produced causes crumbling of the edges of the crystal and the release of aluminium. Whatever the mechanism, the fact that the Al^{3+} is released on washing seems to be well founded, and it will explain some clay phenomena that have long been a source of perplexity, e.g., Mattson's results from cycles of leaching treatments of colloidal clay.

Proof that the positive edge charge is lost on washing is necessarily indirect. One crude test gave as much as was expected. Suppose that the exchangeable aluminium after washing is equivalent in amount to the positive edge charge in *N*-KCl : *N*/1000-HCl before washing (reasonable, but not certain). On re-immersion of the washed kaolin in the acid salt solution, acid will be absorbed in redeveloping the positive edge charge, and Al^{3+} will be replaced by K^+, and if this exchange is complete the titratable acidity of the solution should be unchanged. This is approximately true. However, better information is obtained when the neutral salt is omitted in the pre-treatment. Kaolins were washed with pure acid and then with distilled water, and the suspensions titrated (conductimetric technique) with alkali, so that at the equivalent point the charge was balanced by alkali metal cations, replacing any H^+, Al^{3+}, hydrolised aluminium ions or mixtures of any of these. The variable quantities are the amounts of aluminium hydroxide, $Al(OH)_3$, formed and the amount of alkali needed to convert the hydroxide to aluminate, $Al(OH)_4^{1-}$. In the measurements the aluminate state (4-hydroxyl groups) was detected when the alkali added was equal to four-thirds of the cation exchange capacity (3-hydroxyl groups), from which it is inferred that the permanent charge at the beginning of the titration was balanced by Al^{3+} ions only; that no significant quantity of alkali was needed to neutralise any initial positive edge charge; and that no negative edge charge was produced during the titration. It follows that any change in the properties of an aluminium

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kaolin that occurs when alkali is added in the absence of neutral salt must be caused by some change in the nature or distribution of the ions balancing the permanent charge. One such change was detected in the course of the titrations, reproducing on the clays what is known to occur in titration of aluminium salts: when the titration was done in the presence of cetyl trimethyl ammonium bromide (which displaces the Al^{3+} from the clay surface) the conductivity curve for the clay closely resembled that for the salts. This has two discontinuities, the first occurring at five-sixths of neutralisation and the second (already noted) at four-thirds of neutralisation. The experimental evidence is being prepared for publication, and a discussion of the consequences is in press (1.4). The following is a short description of a new concept that not only explains the results that provoked it, but also explains several other rheological properties of clays.

Modern ideas on the hydrolysis of aluminium ion suggest that polymer ions such as $[Al_6(OH)_{15}]^{3+}$ or $[Al_8(OH)_{20}]^{4+}$ are formed, in which the number of hydroxyl groups is only five-sixths of the number needed for complete neutralisation—giving rise to the first discontinuity in the titration curve. It is now postulated that similar polymer ions were formed in the experiments on clays, and that the charge balance for the kaolin at the five-sixths stage of the neutralisation is that five-sixths of the permanent charge is then balanced by alkali metal cations that can form a diffuse layer, and the remaining one-sixth is balanced by polymer ions in a Stern layer. Because there must be some mobility to account for Al^{3+} ions coming together in groups of six or eight it seems reasonable to suggest that in settling close to the surface they do so in a state of minimum energy, i.e., as far apart as is possible under their mutual repulsions. The result is that the clay particles are positively charged near the periphery by an excess of complex ions in the Stern layer, so acquiring a circular dipole nature that would induce some preferred mutual orientations in assemblies at five-sixths neutralisation. There is evidence to support the inference. Buzágh & Sántó found that the optimum thixotropic behaviour of a "hydrogen" bentonite occurred between 80 and 90% neutralisation ($\frac{5}{6} = 83\%$): Schofield and Samson measured a large decrease in the viscosity of kaolin suspensions just beyond 80% of neutralisation. Other puzzling phenomena in clay physics can be explained (and others reinterpreted) if the idea is generalised to apply to any situation in which diffuse and Stern layers might co-exist, e.g., where the ions are Na^{+} and Ca^{++}, so giving an explanation of the known thixotropic behaviour of clays at a pH too high for positive edge charges to exist. (Cashen)

Soil water movement. A thorough re-examination of the results obtained in measuring water movement through unsaturated porous material (building stones and soils) has been most rewarding. The first interpretation seemed to be adequate, but was acceptable only if the results of subsidiary experiments on diffusion of water vapour in air were set aside as "anomalous". A probable explanation of the anomaly was found, and consequential changes made in the calculation of the transfer constants of the porous systems. Now all the data are self-consistent, and our interpretation of them more confident.

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When a gas or vapour diffuses from a region of high partial pressure to one of low partial pressure it is impeded if it has to pass through a porous medium. The impedance is greater the smaller the pore-space, and for an inert gas such as hydrogen the impedance increases as the porous system gets wetter, because the water is as effective an obstacle to movement as the solid matrix (*Rep. Rothamst. exp. Sta.* for 1961 p. 34). For water vapour, however, there is the possibility (predicted by Philip and de Vries) that liquid water might act as a short-circuit and apparently accelerate the vapour flow through the matrix. The experiments were designed to test the prediction and, if possible, measure the effect.

The porous systems were set up between an evaporating source and a condensing sink with an air gap on both sides, so that all water transmitted reached and left the system as vapour. The first important result obtained is that the conductivity for water increases extremely rapidly over a small range of water content above dryness, far more rapidly than any effect that could be produced by a short-circuit. It seems that, after adsorption requirements have been met, very thin films of water on the surface of the solid possess a high conductivity, and that even in this phase the water is moving through the system as liquid. The second result is that, after this initial rapid increase in conductivity, further change is very small right up to saturation, where the discrepancy between expectation and observation was at least 1,000 fold. The reason lies in the physics of the transfer process. At the uptake side of the porous system the vapour has to condense, giving up latent heat: at the discharge side the liquid has to evaporate, taking in latent heat. As a result there is a temperature difference across the system which effectively decreases the suction difference below that assumed in the computations based on uniform temperature. The effect is as of a back hydromotive force repressing liquid transfer. The magnitude of the temperature difference is of the order of 0·01°C—small enough to go undetected. In the steady state the size of the temperature difference is controlled by the thermal conductivity of the material, and it is possible to calculate the thermal conductivity from the transfer experiments. This is a physical constant of the system directly measurable for the two building stones, and the values obtained were 90 and 120% of those deduced from the transfer experiments, suggesting that the explanation of the very small transfer rates near saturation is probably correct and almost complete.

The implications have yet to be considered in detail, but three possibilities are worth mention. The inhibition of liquid flow near saturation will occur in field soils when conditions are suitable, as they might be in a puffy soil where the crumbs have no extensive physical contact: it might be worthwhile re-examining the results of experiments on the effect of rolling soil. In the drier state it would be useful to know whether the transfer through thin films will carry plant nutrients with it. Most interesting of all, the transition from rapid increase in conductivity to almost a constant value may give a measure of "availability" of water: for the soils examined (all from the Rothamsted farm) the transition occurs when the soil is wetter than pF 4·2, suggesting that this, the conventional lower limit to the available range, is too low, and its use would over-estimate water reserves for plant growth. (Rose)

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Soil water measurement. The neutron meter was used throughout the summer on sites under bare soil and winter wheat, in each of which there was a transpiration balance to estimate changes in water content of the profile directly. The meter behaved very reliably with an accuracy of about ±2%—sufficient to be able to detect the movement of water up and down the profile, even in the top layer of soil. (Long and French)

Agricultural Meteorology

Micro-meteorology. All the equipment was in a crop of winter wheat, near the transpiration gauge that gives a continuous record of water use by the crop. To get more information about conditions inside the crop most of the sensing elements were below crop level, with air temperature and humidity units at five levels, and leaf temperature and ventilation measured at four levels. Soil temperature was recorded at eleven levels 0–50 cm, and the neutron soil moisture meter used, at intervals, over the range 0–100 cm. One of Hirst's dew balances was run near by and showed that on dewy nights towards the end of its period of active growth the wheat absorbed water as though it were blotting-paper. Detailed study of the micro-meteorological records for some of these occasions may be profitable.

The greater detail in new records of ventilation in the crop showed that we oversimplified earlier descriptions, and air movement near the ground (under the main crop canopy) is more rapid than we thought: on calm nights it may exceed the very slight flow in the canopy.

Records of profiles of temperature, humidity and airflow were obtained from three sets of equipment in the hope that the average of the three will remove some of the uncertainties known to arise from persistent hot (or damp) spots in a crop by day. These three sets of equipment are not ventilated, but a fourth is, set up as a trial of technique. A few tests already made suggest that when records from unventilated equipment are corrected for wind speed they are more reliable than those from the ventilated equipment for which correction is unnecessary, particularly at low wind speeds.

Analysis proceeds intermittently, responding to particular needs without any intention of using all the data collected. Examples, in hand or complete, are: provision of digested results for important periods in the development of fungus disease (for Plant Pathology Department); study of profiles over grass for those periods (1959–61) for which energy and water balance of grass are being worked out in the department; a study of the micro-meteorology of haymaking (1960 and 1961); a synthesis of data from potatoes, to meet a request for a conference paper on the subject; and, for sheer physical interest, without any real agricultural significance, what happens on a night of dew and frost. (The onset of dew formation, the freezing of the dew and then, later, the freezing of the leaf sap can be detected in the temperature records.)

A further attempt was made to get at least an indication of vertical air movements over a crop (such as might carry up insects or spores)—with a little success. An array of 60 bi-vane anemometers was set out at ½-metre intervals across the wheat, and, visually, they seemed to be responding to rising hot air. It is hoped to get a film record in 1963. (Long and French)

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Radiometry. On a few clear days in the summers of 1960 and 1961 surface temperatures were measured radiatively with a radiometer borrowed from Imperial College. The results (1.8) show that when soil moisture is adequate for unchecked transpiration the daily mean surface temperature of a green crop canopy is close to mean air temperature, from which it is inferred that all plant surfaces exposed to the same weather will get about the same amount of net radiation.

Solar radiation has been measured with a Kipp solarimeter since 1955 and the records were analysed (1.5). Maximum daily totals of about 700 cal/cm^2 in June agree well with estimates for a clean atmosphere, but around midday in summer the maximum recorded intensity, at about 1·25 cal cm^{-2} min^{-1}, is a few per cent less than expectation, possibly because the lower atmosphere is temporarily "polluted" by soil particles, insects and spores. Monthly totals of radiation at Rothamsted and elsewhere in the British Isles were fitted to a simple formula relating the attenuation of radiation to cloudiness, and for London the radiation loss by pollution was correlated with measured smoke. At Rothamsted, where smoke concentrations measured with a filter loaned by the Department of Scientific and Industrial Research were about three-quarters of those in the centre of the industrial town of Luton 5 miles to the north, the estimated mean loss of radiation in the winter months is between 5 and 10%.

To avoid sampling error when measuring the radiation gradients within crops, a new solarimeter was designed in the form of a tube 3 ft long. Prototypes are being made for tests in the spring.

Analysis of field observations. At the end of 1961 the grass on the experimental site was ploughed and winter wheat was sown on a very uneven seedbed. This seemed a good time for a pause in the measurements of heat, water and CO_2 exchange that were started in 1957, and most of the year was spent in exploring ways of extracting useful information from the miles of recorder chart now accumulated. In a simple electrical analogue of the soil–plant–atmosphere system, fluxes of water vapour and CO_2 correspond to currents, concentration gradients correspond to potential differences and a "diffusive resistance" of the system can be calculated from the ratio of measured gradient to measured flux. A pilot analysis on the measurements made in 1961 gave values for the stomatal and mesophyll resistances of crops in accord with Dr. Gaastra's measurements on single leaves (1.7). Looking ahead, it may be possible to relate these resistances to water deficits in the plant or in the soil, and to describe quantitatively the physiological control of transpiration and photosynthesis.

The uptake of CO_2 by beans and grass in the field was compared with laboratory measurements on single leaves of the same crops. The field crops assimilated CO_2 at about the same rate as two horizontal leaf layers, the upper in full daylight and the lower getting only transmitted radiation. By the end of July the beans stopped accumulating dry matter because the respiration rate of the developing pods was comparable with the assimilation rate (1.6).

Laboratory measurements of assimilation and transpiration. The apparatus built by Dr. Gaastra in 1961 is being extended to measure leaf transpiration and to provide higher light intensities. (Monteith and Szeicz)

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Agricultural meteorology (general). Some of the material in the three papers on the Woburn irrigation experiment was used as the basis for a general survey of the dependence of crop growth on weather (1.9), and also in the report of a study group of the Natural Resources (Technical) Committee on which H. L. Penman served. The report (*Irrigation in Great Britain*, Her Majesty's Stationery Office, price 5*s*. 6*d*.) surveys the past and present of irrigation as a farming technique, and forecasts the probable need of British agriculture for water in about twenty years' time. A short note on the same subject was prepared for a United Nations symposium, planned to take place in Geneva, February 1963 (1.3).

Although our main interest is in making the best use of water when it is supplied, the problems of water supply present a challenge too. After several years of intermittent effort a survey of water use by vegetation was completed, summarising what is known about water use by agricultural crops and trees, and giving extended accounts of experiments in catchment management (1.2). (Penman)

Woburn irrigation experiment 1962. Although transpiration rates during a cold late spring were smaller than usual, rainfall was deficient too, and all four crops responded to irrigation. At the end of the fourth three-course rotation 48 crops have been taken, and of these 33 responded to irrigation by 10% or more, and 19 by 25% or more. *Lucerne*, replacing the grass ploughed up in September 1961, was drilled in April 1962. The first cut (17 July) showed a big response to irrigation, but later the response on the previously irrigated plots was negative at both second (20 August) and third cuts (3 October). There was no irrigation after the first cut. *Spring beans* again benefited—for the fifth time in 6 years. The *Barley* response was the best ever, and it was more obvious than usual that commercial crops were backward. Chemical weed-control on the *Early Potatoes* was a failure, but the experiment provided some useful information on the effect of weed competition on the yield of potatoes. An eel-worm infestation may have decreased yields on all plots. (Penman and Barnes)

TABLE 1

Woburn Irrigation, 1962

Crop	Period	Rain (in.)	Irrigation (in.)	Plot	Yield	
Lucerne	1 May–16 July	3·5	—	O (*a*)	14	Dry matter, cwt/acre
		3·5	3·5	C	26	
	16 July–1 Oct.	7·4	—	O (*b*)	33	
		7·4	—	C	28	
Spring beans	1 May–24 Sept.	9·6	—	O	23	Grain, cwt/acre
		9·6	3·2	C	40	
Barley	1 May–20 Aug.	7·1	—	O	24	Grain, cwt/acre
		7·1	3·0	C	40	
Early potatoes	1 May–16 July	3·5	—	O (*c*)	2·9	Tubers, tons/acre
		3·5	3·0	C	5·8	
	1 May–16 July	3·5	—	O (*d*)	1·8	
		3·5	3·0	C	4·8	

(*a*) First cut. (*b*) Second and third cuts. (*c*) Normal cultivation. (*d*) Chemical "control".

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