Report for 1960

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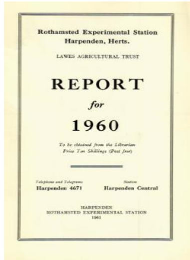
Rothamsted Experimental Station
Harpenden, Herts.

LAWES AGRICULTURAL TRUST

REPORT
for
1960

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Physics Department

H. L. Penman

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PHYSICS DEPARTMENT

H. L. PENMAN

Dr. R. K. Schofield died on 8 June 1960. He joined the department 32 years ago, was head of it from 1946 to 1954, and then spent two years as head of the Chemistry Department before taking up a Readership in Oxford.

D. Rijks completed his training period in January and is now working in Uganda. Dr. K. Yabuki, University of Osaka, Japan, came in August to work on agricultural meteorology; Dr. G. Contreras, a Ramsay Memorial Fellow from Madrid, came in December to work on soil water.

W. C. Game was awarded a B.E.M. in the New Year Honours List (1961), an event giving great pleasure to all who know of his 50 years of faithful service to the Station, particularly as meteorological observer.

AGRICULTURAL METEOROLOGY

Woburn Irrigation Experiment, 1951–59

The third three-year cycle was completed in 1959, and it is expected that a synoptic review of the nine years' data will be published in 1961. The experiment has been doubly useful. First, as an exercise in agronomy, it has shown how farm crops respond to irrigation, and this is the aspect to be outlined here. Second, of equal interest and possibly of greater importance, it has provided raw material for studying dependence of growth on weather, but this aspect will be ignored now because it would need a long introduction and many line diagrams.

The ever-increasing number of farmers who use irrigation have a guide to management in a technical bulletin, published by the Ministry of Agriculture and based on earlier Rothamsted work (*The Calculation of Irrigation Need* ed. R. T. Pearl. London, H.M.S.O., 1954). It may be helpful to link the Woburn experiment with the bulletin, which gives estimates, based on weather data, of average monthly potential transpiration (April to September) for sub-counties in England and Wales, and compares the six-month totals with the corresponding summer rainfall for the same areas. Making the arbitrary decision that a summer is one of " irrigation need " when the estimated transpiration exceeds the rainfall by more than 3 inches, the predicted frequency of need at Woburn is near seven years in ten and even greater to the south and east. This is a purely meteorological assessment, based on a guess at a plant factor which is unlikely to be true for all species, even if true for one; it makes no pretence at predicting how any kind of crop will respond if part or all of the rainfall deficiency is made good by irrigation. " Does irrigation work? " can only be answered in the field, and the Woburn experiment was designed to get relevant information on farm crops, watered at times and in amounts

C

determined by weekly estimates of potential transpiration calculated from weather data collected on the site of the experiment.

Of the nine summers, five satisfied the meteorological specification of " irrigation need ", somewhat fewer than expected, partly for local reasons peculiar to the site, and partly because of the natural variability of weather. Growing four crops per year, twenty were taken off in the five drier years, and of these only two did not respond to irrigation. Of the sixteen crops grown in the wetter years only four responded positively to irrigation, and a few responded negatively when, after early irrigation, there was enough summer rain to cause leaching. Broadly, the meteorological forecast of irrigation need has proved to be a good general farming forecast, but, as succeeding paragraphs show, some qualification of the general statement is needed for each crop.

The experimental area is in four main sections, each with twelve plots permitting three-fold replication of four treatments. Series IV carried a ley throughout, first, 1951–53, as a grass/clover mixture (main components, S26 Cocksfoot and S100 White Clover), and then, 1954–59, as a pure grass stand (S37 Cocksfoot). On Series I to III there were three three-course rotations: 1951–53 early potatoes (Ulster Chieftain), sugar beet (Klein E), barley (Plumage Archer); 1954–56, main crop potatoes (Majestic), sugar beet, barley (Herta); 1957–59, spring beans (Spring Tick), sugar beet, spring wheat (Peko). Each crop got the basal fertiliser dressing thought best for it, with one variant (usually an extra nitrogen dressing) on half plots. Most of the watering was in doses of 0·5 inch, the four treatments always including unwatered control plots (O treatment) and plots kept near capacity (C treatment). Intermediate treatments (A and B) varied greatly, and sometimes were sacrificed to permit another fertiliser variant or a management treatment. The leys were cut at three- or four-week intervals throughout each summer—as though the crop were being managed for grass drying.

There is no common pattern in the summary tables that follow, because the points of interest vary from crop to crop. Most of them give total yields over several years, with details and decimals suppressed except where they may be helpful. Irrigation, I, is expressed in inches, and growth in the normal field unit, usually cwt. or tons/acre.

TABLE 1

Leys, 1951–59

N_2 treatment

Total growth, G, in cwt. dry matter per acre

Treatment		O	A		B		C		Mean
		G	G	I	G	I	G	I	
1951–53 (3 years)	Grass	175	193	—	203	—	205	—	—
	Clover	24	29	—	41	—	50	—	—
	Whole crop	199	222	5·4	244	8·6	255	14·2	—
Response/inch	Grass	—	3·3	—	3·2	—	2·1	—	2·7
	Clover	—	0·9	—	2·0	—	1·8	—	1·7
	Whole	—	4·2	—	5·2	—	3·9	—	4·4
1954–59 (6 years)	Grass	353	388	9·5	411	21·4	444	31·0	—
Response/inch		—	2·7	—	2·7	—	2·9	—	2·8

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Results are given for the N_2 treatment only, as no other was consistently applied throughout the 9 years. For the first 6 years there was N_1 at half the N_2 rate: for the last three, there was N_4 at twice the N_2 rate. The nitrogen was applied in spring and after every cut except the last, with $N_2 = 0{\cdot}3$ cwt. N per acre. The number of cuts varied up to eight per summer, and the average total summer application can be taken as close to 2·0 cwt. N per acre.

Both grass and clover responded to irrigation, the clover proportionately more than the grass even at this rate of nitrogen fertilisation. At the lower rate (N_1) the proportion of clover in the irrigated sward was greater than at N_2. The mean annual growth and response of the grass to irrigation were about the same in the two periods. In the later period, when nitrogen dressings were compared in the ratios 1: 2: 4, the corresponding growth rate ratios for the fully irrigated plots (C treatment) were 1 : 1·25 : 1·60, while for the control plots the spread was smaller. In *effect*, doubling the nitrogen dressing behaves as though it adds 0·5 inches to soil water reserves. To maintain maximum growth, the soil must be kept near field capacity (the tolerable moisture deficits being 1·0, 1·5 and 2·0 inches for treatments N_1, N_2 and N_4 respectively), and it is because of this that the response per inch (bottom line of table) is constant. These responses would be increased by 50 per cent were the data used restricted to those occasions when subsequent rain did not render irrigation superfluous. Within the period very good responses to irrigation were obtained in 1951, 1952, 1955, 1957 and 1959; good responses in 1953 and 1956; and zero responses in 1954 and 1958.

TABLE 2

Sugar beet, 1951–59

Total growth per acre (9 years)

	O		Best treatment (Total I = 22 inches)	
	N_1	N_2	N_1	N_2
Clean beet, tons	130	146	146	162
Tops, tons	82	108	93	122
Sugar, cwt.	470	521	527	582
Response/inch, sugar	—	—	2·6	2·8
Sugar %, mean	18·0	17·8	17·9	17·7

This is the most difficult crop of all. Whereas with grass attention need be paid only to the leaves, and with potatoes to the tubers, with sugar beet attention must be paid to tops, roots and sugar content, all of which may react differently to watering and fertiliser treatment. In addition, year-to-year fluctuations in virus disease produce much bigger changes in yield than does management.

The nitrogen dressings were $N_1 = 0{\cdot}4$, $N_2 = 0{\cdot}8$ cwt. N per acre for the first 6 years, increased to 0·6 and 1·2 cwt./acre for the last three. The scatter in the yields was such that the change was not detectable, and there is no separation in the table. In the belief that better management of sugar-beet irrigation can be achieved, the table is selective and gives the total yields for the treatments that

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gave the best yield of sugar each year: in five of the years this was not the treatment that got the most irrigation. A deficit of 2 inches at six weeks after singling seems to be tolerated without any major effect on yield (and may, in fact, be desirable to encourage root extension), which is in accord with known good commercial irrigation practice. Out of 30×2 sub-treatments harvested in the 9 years only four at N_1 level, and two at N_2 level, gave less than 80% of the yield of the best treatment in that particular season. Other broad conclusions are perhaps best considered as guides to further inquiry: The most consistent response to extra nitrogen is in the yield of tops, and it is greatest after winters of greatest leaching, and hence dependent on the irrigation treatments of the previous year. The growth of the tops seems to depend on watering treatment from the time of sowing onward, that of the roots on watering treatment from time of singling onward, and the sugar content (%) is almost independent of watering treatment or nitrogen treatment, but increases with the amount of sunshine in the four months after singling. As the table shows, the response of the crop to water is independent of nitrogen treatment, and on average—but only as an average—it is about the same as the response to doubling of the nitrogen dressing, at about 11%. Within the nine years very good responses to water were obtained in 1952, 1955 and 1959, an average response in 1957, and zero, or slightly negative responses in 1953, 1954, 1956, 1957 and 1958.

TABLE 3

Potatoes, 1951–56

Total yield of tubers (tons/acre)

	O		(a)			(b)			C		
Earlies	N_1	N_2	N_1	N_2	*I*	N_1	N_2	*I*	N_1	N_2	*I*
1951–53 (3 years)	20	22	22	26	2·1	26	29	4·6	29	34	6·9
Response/inch	—	—	1·1	1·7	—	1·3	1·5	—	1·4	1·8	—
Maincrop											
1954–56 (3 years)	39	45	44	50	2·4	45	51	6·6	47	55	9·0
Response/inch	—	—	2·0	2·2	—	0·9	1·0	—	0·9	1·1	—

The " early " potatoes were harvested about mid-July, and the haulms of the main crop killed in September. Two levels of nitrogen were $N_1 = 0{\cdot}5$, $N_2 = 1{\cdot}0$ cwt. N per acre, the basal PK was the same in both rotations, and the main crop potatoes also got 15 tons of dung per acre. One of the extraordinary results of the detailed analysis—probably fortuitous—is that in spite of this major difference in manuring the two sets of data can be fitted by a common growth curve.

Potatoes respond well to irrigation, and, like grass, grow best when the soil water content is kept close to field capacity, a major check to growth occurring whenever the deficit exceeds 1·0 inch. For the table, the irrigation treatments were arranged in ascending order of magnitude, but they are all included. The early crop responded better to irrigation at the higher nitrogen dressing, whereas the main-crop response was almost independent of nitrogen dressing. Irrigation prolonged the period of leaf development, and delayed flowering and death of tops. Within the six years very good responses were obtained in 1951, 1952 and 1955, a good response in 1953, and no response in 1954 and 1956.

The primary reason for including cereals was to make the rotations realistic. The nitrogen treatments for the barley were $N_1 = 0{\cdot}2$, $N_2 = 0{\cdot}4$ cwt. N per acre, and for the wheat were $N_1 = 0{\cdot}4$, $N_2 = 0{\cdot}8$ cwt. N per acre. Because of the change in variety

TABLE 4

Spring cereals, 1951–59

Total yield of grain (cwt./acre)

	O		Best treatment		
Barley	N_1	N_2	N_1	N_2	*I*
1951–53 (3 years)	67	83	75	90	6·1
1954–56 (3 years)	88	108	96	114	3·4
Total	155	192	172	204	9·5
Response/inch	—	—	1·8	1·3	—
Wheat					
1957–59 (3 years)	68	70	81	91	7·9
Response/inch	—	—	1·7	2·6	—

in 1954, the barley yields are given separately for each rotation, and, again acting on the presumption that better knowledge will circumvent waste of water, the best yielding treatments have been chosen to show what irrigation can achieve. It is clear that extra nitrogen is much more effective than irrigation in increasing barley yields, and the lower the nitrogen level, the greater the response to irrigation. Wheat, in clear contrast, seems to need the water before it can respond to extra nitrogen. Good responses were obtained in 1951, 1956, 1957 and 1959, about average in 1952, and zero or negative responses in 1953, 1954, 1955 and 1958.

TABLE 5

Spring beans, 1957–59

Annual yield of grain (cwt./acre)

	O		C		
	D_0	D_1	D_0	D_1	*I*
1957	11·8	14·0	25·6	25·7	4·0
1958	15·3	14·4	16·0	14·8	1·0
1959	8·2	9·0	21·0	21·0	4·5
Total	35	37	63	62	9·5
Response/inch	—	—	2·8	2·5	—

The basal manuring was PK (*no* nitrogen) with dung as variant ($D_1 = 12$ tons/acre). Spraying against aphids was included as a treatment in 1957 and 1959, and though there were minor interactions of irrigation, dung and spraying treatments in the dry summer of 1959, they are ignored in the table. There is no doubt that beans respond to irrigation in a dry summer, and in 1959 the plants grew well over 6 feet tall, over-topping the spray lines for a while. With this great inter-node expansion there was maintained vegetative growth and delayed ripening. The crop responded positively to dung only when water supply was limiting growth, and the response was zero or negative when the soil was kept moist, either by irrigation in 1957 and 1959 or by rain in 1958.

As already stated, the test at Woburn suggests that the "Frequency of Need" map in the technical bulletin is a good guide to general farming need for summer irrigation. For grass and potatoes it underestimates the frequency, for beans it may be about correct, for sugar beet and cereals it is probably an overestimate. Whereas the first three crops seem to need water at all stages of growth, the chief threat to sugar beet lies in a dry late summer, and that to cereals in a dry early summer. Not all of the unnecessary irrigation in the nine years was caused by the legitimate conditions of an experiment: much of it was unavoidable, and this type of waste will continue in experiments and in farming practice until weather can be forecast for the next week or two. It is reassuring to know that development of such medium-range forecasts is an important part of the research programme of the Meteorological Office.

Woburn irrigation experiment, 1960

Until the first week of June the equipment was in use every week: thereafter it was idle. All crops responded. *Grass:* Nearly all the response was in the first three cuts (up to late June). *Barley:* Again, a small increase in nitrogen dressing was more efficient than extra water. *Winter beans:* The unwatered yield was as good as the best previously obtained with irrigated spring beans: the effect of irrigation was surprisingly great. *Early potatoes:* The results are for plots given normal cultivations. Six of the twelve plots had minimum cultivation and a "Simazine" spray a week after planting. All yields from these plots were smaller than those in the table, by 1·9 tons/acre, unwatered, and by 2·4 tons/acre, irrigated. (Penman and Barnes.)

TABLE 6

Woburn Irrigation, 1960

Crop	Period	Rain (inches)	Irrigation (inches)	Plot	Yield	
Grass	25 Apr.–3 Oct.	14·8	—	ON_2	84	Dry matter, cwt./acre, 8 cuts
				ON_4	93	
		14·8	3·8	CN_2	95	
				CN_4	109	
Barley	25 Apr.–8 Aug.	8·3	—	ON_1	22	Grain, cwt./acre
				ON_2	30	
		8·3	2·0	CN_1	26	
				CN_2	33	
Winter beans	25 Apr.–8 Aug.	8·3	—	O	26	Grain, cwt./acre
		8·3	3·5	C	40	
Early potatoes	25 Apr.–11 July	6·1	—	ON_1	9·1	Tubers, tons/acre
				ON_2	10·4	
		6·1	2·2	CN_1	10·9	
				CN_2	13·0	

Micro-meteorology

Measurements of temperature, humidity and wind profiles over grass, started in spring 1959, were maintained throughout the winter (for the first time) and are still in progress. Processing of the data proceeds slowly, and analysis will be a formidable task. During hay-making on the site in June and August rates of drying were measured by sampling, and these will be compared with estimates from profile measurements taken at the same time. Most of the water (about $\frac{3}{4}$) evaporated during the first full (sunny) day of drying, and on the clear night after it about $\frac{1}{4}$ of this returned as dew. On subsequent nights about half of the daytime evaporation returned as dew.

Improvements in instrumentation continue, the main effort being for wind measurements in crops, wind direction, ventilation of psychrometers and a better form of output for the neutron-scattering equipment used in soil-water measurements. (Long.)

Radiation balance

The amount of energy used in evaporating water from a closed crop canopy is only slightly less than the *net* radiation received by the canopy. The hour-by-hour changes in assimilation of atmospheric carbon dioxide are strongly correlated with *solar* radiation. Knowledge of the relation between net radiation and solar radiation would therefore seem to be fundamental to any study of the relation between transpiration and growth, and could be relevant to agriculture outside the temperate zone in which the knowledge is being sought. Rothamsted records for cloudless daylight hours show a linear relation between net radiation and solar radiation, which can be interpreted in terms of a heating coefficient that allows for changes in long-wave loss with changes in surface temperature (1·7). Measurements with a Linke–Feussner radiometer (kindly lent by Prof. P. A. Sheppard, Imperial College) confirmed that both surface temperature and long-wave radiation exchange are linearly related to net radiation when the sky is clear. Similar work remains to be done for cloudy hours, but as an intermediate step an empirical formula has been devised to give a value of long-wave exchange in terms of screen vapour pressure, screen temperature and cloudiness (1·6). When applied to sites that have records of short-wave radiation, the formula suggests that there is little variation in mean annual values of net radiation between northern Scotland and southern England. There is here some conflict with estimates of annual evaporation for the same sites, and both sets of estimates need further probing.

Water balance

In the fourth year of use of the field balance the crop was grass, sown in spring 1959. The early 1959 records, examined to get measures of evaporation from bare soil, show, as expected, that after heavy rain the ratio of evaporation from the soil (E_s) to that from an open water tank of about the same size (E_o) is close to unity. When the deficit reached only 5 mm. E_s/E_o decreased to 0·4, an unexpectedly low value. The ratio increased on days after dew nights that added 0·3–0·4 mm. of water to the soil. Laboratory experiments are planned, to link these field observations with previous work of Penman and current work of Rose on vapour transfer.

A second field balance was acquired, and simultaneous measurements of evaporation from two crops will start in 1961.

Carbon dioxide balance

Further analysis of the 1958 data for sugar beet yielded estimates of the diffusion resistances governing uptake of carbon dioxide and discharge of water vapour. The dependence of gross assimilation on radiation intensity for this field crop accords closely with that found by Dr. P. Gaastra in Holland, working on single leaves in a laboratory.

In 1960 carbon dioxide gradients were measured over grass, and fluxes calculated from wind records taken by Long. At the end of May the midday peak of gross assimilation rate reached 0·6 mg. cm.$^{-2}$ hr.$^{-1}$, while the crop height was increasing by 2·5 cm./day. After cutting in June growth was slower, and the peak assimilation rate was only 0·4 mg. cm.$^{-2}$ hr.$^{-1}$, equal to the rate calculated for sugar beet in August 1958. With new equipment, installed in late summer, concentration differences are now measured over five steps from soil surface up to 1 m. above. Daytime records show that carbon dioxide moves into the crop canopy from the soil and from the atmosphere, and two methods of direct measurement of the flux from the soil are being tried. Progress is good, and there are hopes of getting hourly values in addition to the daily totals now being measured.

Radiometry

The small portable solarimeter, working into an electrolytic integrator, gives daily totals of radiation at Rothamsted agreeing well with those from the standard Kipp instrument. Between January and July the standard deviation in weekly totals was only 40 cal. cm.$^{-2}$. A similar unit was installed at Woburn in June, and since then there has been very little difference in weekly totals of radiation at the two stations. Six units, set up in a crop of oats, showed important diurnal changes in the distribution of radiation with height; two others, modified to accept only visible radiation (0·4–0·7 μ), were used to measure light distribution in a crop during an experiment by the Botany Department (see p. 97).

Two simple types of net radiometer were made, one of which requires no ventilation. A general account of these, and other radiation instruments devised over the past few years, is in preparation. (Monteith, Szeicz and Yabuki.)

Soil Physics

Electrical charges on clays

Clays are unstable if they are first given an acid treatment and then washed with distilled water, because the positive charges on the edges of the clay particles produce electrical stresses that are too great for the strength of the structure. Exchangeable aluminium is always present after such treatment. It has now been proved that the newly exposed edges of the clay particles are uncharged. Decomposition may be caused by direct acid attack, and experiments are in progress attempting to distinguish between the two types of breakdown.

Phases in the uptake of cetyl trimethyl ammonium bromide

(CTAB) by clays can be detected from conductivity measurements. The CTAB itself has a critical concentration in solution at which it forms micelles, and in clay suspensions this critical concentration is not reached until CTAB cations and ion pairs have been adsorbed in amount equivalent to nearly three times the cation-exchange capacity of the clay. Assuming the CTAB molecule has an area of cross-section of 41 $Å^2$, estimates of the surface areas of clays are 200 $m.^2 g.^{-1}$ for an illite, and 500 $m.^2g.^{-1}$ for a bentonite, the latter being smaller than the theoretical figure of 800 $m.^2g.^{-1}$. The discrepancy may be accounted for by incomplete dispersion of the bentonite. For Peerless kaolin the area estimated in this way is of the same order as that found by measuring low-temperature gas adsorption (17 $m.^2g.^{-1}$). (Cashen.)

Soil structure

Plots ploughed after 4 years under ley or fallow were planted with spring beans. Given the same cultivation, the amount needed to get a tilth after grass was too much for the former fallow plots, and these puddled badly, so that differences in growth of the beans must be attributed partly, at least, to conditions imposed by cultivation rather than wholly to pre-treatment. From germination to harvest the plants on the puddled plots were inferior, with restricted root development and poorer nodulation. Although the structural units of all plots had the same porosity, the aggregates after the leys were much more stable to wetting than those after fallow, and formed a less rigid root-bed while the soil was dry. This double improvement in root environment was achieved without very much of the residual organic matter from the grass being intimately incorporated within the soil crumbs.

Soil aeration

Having completed the work on diffusion in dry porous materials, the effects of a liquid phase in the system are now being measured (1.4). When there is no swelling a clear general picture emerges: at the water content that just saturates the soil aggregates, the aggregates behave like " dry " solid particles of the same shape. As more water is added and the inter-crumb space is filled, the diffusion constant of the system decreases, being proportional to the fourth power of the remaining air-filled pore-space. A change of water content in the opposite direction gives results that depend on the origin and previous history of the crumbs: as the crumbs are dried, the diffusion coefficient increases because extra channels are opened, but the increase is small, and in no soil so far examined has the maximum increase per unit of crumb pore-space (at complete dryness) been as great as the value per unit of inter-crumb pore-space at crumb saturation. Macro-aeration of soil in the field must depend almost entirely on the inter-crumb pore-space, and between water-logging and field capacity it will be subject to the fourth-power law, and will not be significantly increased when a soil moisture deficit is established by transpiration. Further study of the micro-aeration of the crumbs offers great possibilities, ranging from an empirical specification of a " structure " factor to an understanding of the physics of gas exchange near the surfaces of roots and other biotic components of the soil.

When swelling occurs in a confined sample the inter-crumb pore-space is decreased. The change is not completely reversible on drying, and the degree of hysteresis depends on the strength of the crumbs when wet. (Currie.)

Soil water

Measurement of water-vapour movement in unsaturated media continued, using building stones and sieved field soils as test materials. The presence of liquid in the system increased the transfer rate above that calculated for pure vapour diffusion. In parallel there was a complete series of measurements of the diffusion of hydrogen through the same materials (Currie technique), and from the two sets of data it should be possible to sort out the interactions of movement as liquid and movement as vapour. As a welcome by-product, the experimental technique provides a quick and reproducible way of measuring water potentials in the range pF 2·5–5·6.

The transfer rate per unit *total* potential gradient is less when dissolved salts are present than when they are not. The magnitude of the decrease can be calculated provided the salt concentration and ionic diffusion coefficient are known. Measurements confirm the dependence on concentration, and lead to estimates of ionic diffusion coefficients in saturated building stones that are concordant with gaseous diffusion through the same stones when dry. (Rose.)