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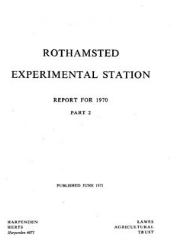
Rothamsted Experimental Station Report for 1970 Part 2


ROTHAMSTED
EXPERIMENTAL STATION
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PART 2

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Irrigation at Woburn - VII

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Irrigation at Woburn—VII

H. L. PENMAN

Preamble

A Working Group of the Agricultural Research Council, looking at important future problems, used the term 'speculative' for research with no immediately obvious practical outlet either in agriculture or farming. The term is unfortunate in its association with gambles and guesses, but what it refers to, presumably, is that part of the research effort that is put into getting basic knowledge of the raw material, and of the enemies of the industry. Why the Research Council for the country's chief industry should seem to need special pleading for this kind of work is puzzling. Some of it pays for itself merely by occasional success in stopping expensive nonsense at source: some pays for itself in restricting or expanding the range of validity of empirical results from *ad hoc* experiments: much will pay for itself when the industry's techniques have caught up with research results sufficiently to be able to exploit them: and some can trigger a new technique, or greatly expand the use of a technique not previously thought necessary in a British environment. This, in essence, is the story of irrigation in Britain. Twenty years ago the area of farm crops irrigated was about 20 000 acres: now it is near 300 000 acres. The Rothamsted part in this had two components, visible and invisible. The visible part is in guidance material from the Ministry of Agriculture, Fisheries and Food in its *Bulletins* 138 and 202 and *Technical Bulletins* 4 and 16. The invisible part is, in some ways, even more important. The job needs water, and someone has to supply it, usually at times when demands from other consumers are greatest and reserves are least. Water authorities have been very ready—often eager—to try to meet this agricultural demand for water, and the Ministry has encouraged them to do so because both parties knew that the demand was based on 'speculative' research confirmed by well designed field experiments. For the same reason the Central Advisory Water Committee, in its thorough review of Britain's water resources and future needs, accepted this new use of water as a fair demand that Water Authorities must try to satisfy, and set up a Technical Sub-Committee to estimate the probable demand by 1980. The Committee Report (*Irrigation in Great Britain*, H.M.S.O. 1962) is, in design and effect, a short text-book on the subject, giving the bases, in physics and plant physiology, for water use by plants, showing why, where, and when summer water shortages occur, summarising the information then available on crop responses to irrigation (farm crops, vegetables, fruit) both in terms of agriculture (increased yield) and farming (increased profit), and estimating, against the then pattern of land use, the probable area that might be worth irrigating some day. Agriculturally—by including a lot of grassland—the area is 1 500 000 acres: more realistically—as farming—the area is about 500 000 acres, and this might well be reached in another ten years or so.

Part of the evidence used by the sub-committee came from the Woburn irrigation experiment: an account of the first nine years' results 1951–59 was published in three papers (Penman, 1962). A second group of three (Penman, 1970) completes the record, 1960–68. The two groups are numbered I to III, and IV to VI: these numbers will be used for simplicity in cross-references in this digest of 18 years of field measurements.

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Introduction

The raw materials of agriculture are the green plants, the soil, and the weather. For the water story it seems very obvious to start with 'What happens to the rain?' (Keen, 1939), but in this and a later review (Keen, 1940) it is almost as obvious that there is not much reward in the search for rain/growth relationships. Groping for reasons transforms the question to 'What happens to the sunshine?', which can be answered in a way that permits forecasting and backcasting. Ignoring meteorological complexity, the simple answer is: From a green farmscape about one-quarter of the sun's energy is reflected (Monteith, 1959): of the non-reflected energy, about half is used in evaporating water and the other half is used in various processes of energy transfer from the surface to the atmosphere. (To give scale, during a fine mid-summer week in S.E. England the average solar radiation income is near 480 cal cm^{-2} day^{-1}, and with one-quarter reflected there are 180 cal cm^{-2} day^{-1} each for evaporation and for other sinks. At 600 cal g^{-1} for the energy of vapourisation, the estimated evaporation rate is 0·3 g cm^{-2} day^{-1}, or 3 mm per day in the equivalent rainfall unit). The more exact working answer needs some quantification of the energy transferred in the other processes and this can be achieved with knowledge of air temperature, air humidity, wind speed, and duration of bright sunshine (used indirectly as a measure of cloud cover). These are the elements measured—as routine—at weather stations, and thus it became possible to use past climatological records to calculate seasonal energy balances in a way that left evaporation as the only unknown. The result of a group effort was the production, by the Ministry of Agriculture, Fisheries and Food in 1954, of *Technical Bulletin* No. 4, on *The Calculation of Irrigation Need*. Figure 1 is from this bulletin, and shows how often summer rainfall (April to September, inclusive) falls short of calculated evaporation by more than 75 mm. The map is purely climatological: it cannot indicate how plant growth would be affected by attempts to manage this deficit. For this field experiments were needed, and after three years co-operative work with the British Sugar Corporation on two commercial farms (Penman, 1952), the Woburn experiment was started in 1951, with two objectives:

(i) Practical—to measure the response of ordinary farm crops to supplementary watering;

(ii) Speculative—to seek crop/weather relationships that might be applicable to other sites, crops and climates.

Basic ideas

Understanding of the field results, and their application to farm practice, will be greatly helped by a short account of some of the speculative ideas added to some basic concepts now generally accepted as a good working hypothesis in the physics and physiology of plant/water relations.

One physical boundary condition is that there is a large area of a short crop completely covering the ground, and that it is actively growing. (There are special problems in small areas, as in most field experiments; for tall crops, e.g. trees; for incomplete cover, e.g. sugar beet and potatoes at early stages; and for senescent or maturing crops.) When the water supply around the roots is adequate, the rate of water use is dictated by the weather, with plant factors having only a small effect, and soil factors negligible. This weather-determined rate is called the 'potential evaporation' or 'potential transpiration' rate and is given the symbol E_T (originally intended as the evaporation rate from a *turf* surface). In effect, E_T is the evaporation rate from an extended area of short grass kept

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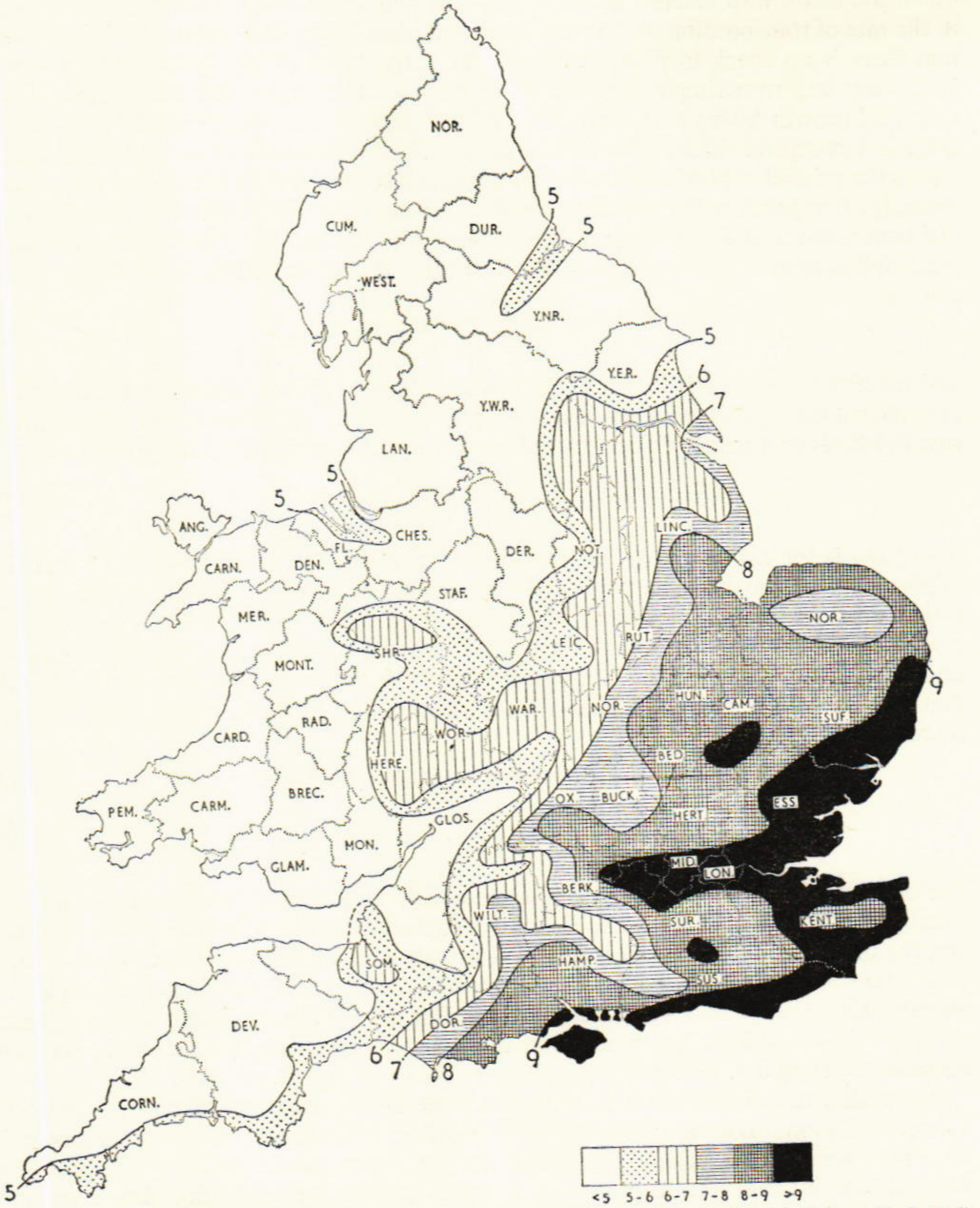

FIG. 1. Meteorological estimate of the frequency of irrigation need (years in ten). From: *Tech. Bull. Minist. Agric. Fish. Fd* No. 4, 1954. (H.M.S.O.)

in the vegetative phase of development, and it is not unreasonable to look for first tests of ideas on such a sward.

Starting from soil at field capacity, and in the absence of rain or irrigation, the transpiration stream will dry the soil at and near the plant roots, setting up stresses in both soil and plant. The soil stress may affect the ability of the roots to collect more water

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(i.e. a soil factor now comes in): the plant stress may affect the physiology, and, through it, the rate of transpiration, or the rate of assimilation. From field experience it is obvious that there is no check to plant growth in the early stages of soil drying, and thence it is an easy step to a simple hypothesis—at least worth a trial—that this period of unrestricted growth lasts up to a threshold of soil dryness, and that beyond the threshold there is a complete check. This threshold is defined quantitatively as a limiting deficit, D_l, as the rainfall equivalent of water that must then be added to restore the soil to field capacity. It represents the amount of water stored in the soil profile that the soil itself can contribute to plant growth: to get a measure of it, crop by crop, is the major technical objective in irrigation experiments. For rain, R, and irrigation, I, the deficit at any time is

$$D = E_T - (R + I) \tag{1}$$

and the simple hypothesis is that while D is less than D_l growth is unchecked, and while D is more than D_l *and still increasing* then growth is zero. An extension of the argument (see IV) leads to a value of the active evaporation contributing to plant growth as

$$E_A = E_T - D_m + D_l \tag{2}$$

where D_m is the maximum deficit reached during the period considered. Note that this implies that as the profile is rewetted—whatever the value of D—all evaporation is active. Again as another working hypothesis—one object of the work is to find field evidence—the growth rate, as botanical yield, is proportional to the potential transpiration rate when water supply is non-limiting, and the limiting deficit concept would add that total growth is proportional to the total active transpiration. Hence, with symbols representing totals,

$$Y = kE_T \qquad \text{while} \qquad D_m \text{ is less than } D_l \tag{3}$$

$$Y = k(E_T - D_m + D_l) \text{ otherwise.} \tag{4}$$

The effect of irrigation, I, is to decrease the deficit, so the maximum, D_{mI}, for an irrigated plot will always be less than D_{mO} for a control plot, but seasonal weather changes and the timing of irrigation operations will usually produce the result that $D_{mO} - D_{mI}$ is *less* than the irrigation applied (see Table 10). Further, for maximum irrigation, as planned, the value of D_{mI} will be less than D_l. For both reasons, the measured response, as $(Y_I - Y_O)/I$, will be less than k. In the limit, k represents the maximum possible response to irrigation, obtained when $D_{mO} - D_{mI} = I$ and $D_{mO} \geqslant D_l$.

It is easiest to estimate k for a ley, cut at intervals to give accumulated values of Y. Values of E_T and D_m are calculated from weather records, and the only unknown is D_l. There are various ways of estimating D_l, but it can usually be done by inspection and adjusted by trial until a plot of Y against E_A gives a straight line. For a ley, cut perhaps six times in a year, with four irrigation treatments (O, A, B, C, say), there will be 24 points to make coherent. Usually, some of these will correspond to duplicate treatments and will show a scatter inescapable in field measurements: if the processed points fit a straight line with not much more than the same scale of scatter, then the processing can be regarded as successful, the slope of the line can be used as a value of k (the maximum possible response), and the value of D_l chosen to achieve coherence can be accepted with some confidence. This is the quantity needed to give practical guidance to farmers.

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The experiment

The ideas and equations will become much more real when the symbols turn into numbers, and in the next section the results for a ley, 1951–53, will be examined in some detail.

The experiment was set out in the south-east corner of Butt Close on the northern edge of the Lower Greensand at Woburn. The area was roughly 150 × 100 m, with a good open exposure to west and north, and also to the east except for a few tall trees, but was very sheltered all along the south side: it is probable that estimates of water need were somewhat smaller than they would have been for a more exposed site, and the meteorological frequency of irrigation need a little smaller than Fig. 1 predicts. The soil, a sandy loam, contains enough clay to give coherent clods in the top foot, but below it is loose unconsolidated sand. The infiltration capacity is not very great, and care was needed to avoid run-off when irrigating row crops.

The area was divided into four series (I to IV) each divided into 12 plots giving three-fold replication of four possible watering treatments. Though it was expected that there would be important interactions between water and fertiliser treatments the degrees of freedom available were too few to permit much variation (and the plots were too small anyway). Each crop was given the basic fertiliser treatment conforming to recommended good practice, with one variant introduced by splitting plots. It was usually an extra nitrogen dressing. Weather records were taken on the site or at the farm about 350 m away. The unit of time was the week, ending on Monday morning, and irrigation instructions were received at Woburn on the Wednesday.

For the first 15 years, up to 1965, Series IV carried some sort of ley and the other series had varied three-course rotations. From 1966 onward the emphasis was on management, with series IV and I used for a long term potato experiment on cyst nematodes, while the other two were used for *ad hoc* experiments, including trials of the dwarfing compound CCC (Humphries, 1970). Some of the results 1966–69 are relevant to the present survey, but not all.

The general watering policy was that each unit block of four plots should carry an unwatered plot (*O*), and one fully irrigated (*C*) on which the aim was to keep the deficit at less than 2·5 cm: occasionally, unavoidable delays allowed the deficit to increase beyond 2·5 cm, and sometimes rain quickly decreased it to zero with a surplus as 'estimated drainage'. The other two plots, *A* and *B*, had regimes intermediate between *O* and *C*; for annual crops one would be at the *C* rate early in the season and the other zero, and then the 'early' plot would get no more and the other would get the same treatment as *C* 'late' in the season. The division between 'early' and 'late' was usually based on some easily recognised phase in crop development, e.g. ear emergence for cereals, flowering in potatoes and beans.

Leys

Particular, 1951–53 (Table 1). The seeds mixture was broadcast on 24 April 1951 with components: Italian ryegrass (6), S26 cocksfoot (16), S100 white clover (4) and Canadian Alsike (2). Next day basal fertiliser was applied: P_2O_5 and K_2O at 0·6 cwt acre^{-1}. There was no nitrogen applied until after the first cut on 11 July, and then it was as 'Nitro-Chalk' at two intensities: N_1, 0·15; N_2, 0·30 cwt N acre^{-1}. These dressings were repeated after the second and third cuts, 13 August and 4 September, but not after the fourth cut on 9 October. In 1952 the basal PK dressing was applied on 21 March—no nitrogen—and the N_1 and N_2 dressings applied after the first four cuts (29 April, 19 May, 16 June,

TABLE 1

Grass/clover, 1951–53

Sown 24 April 1951. $N_1 = 0{\cdot}15$, $N_2 = 0{\cdot}30$ cwt acre^{-1} N per application

		N_1					N_2					
			Grass/clover					Grass/clover				
Year	Number of N applications	Best yield t ha^{-1}	*O*	*C*	Response t ha^{-1} cm^{-1}	k_1	Best yield t ha^{-1}	*O*	*C*	Response t ha^{-1} cm^{-1}	k_2	k_2/k_1
1951	3	6·4	2·4	1·4	0·23	0·38	7·4	7	2·3	0·16	0·48	1·26
1952	4	10·4	3·9	2·3	0·29	0·25	11·0	27	8	0·31	0·26	1·04
1953	1 + 6	12·2	1·9	1·6	0·08	0·28	13·5	5	3·9	0·13	0·32	1·13

General note, for all tables and figures.

1 t ha^{-1} $\simeq$ 8 cwt acre^{-1}

1 t ha^{-1} cm^{-1} $\simeq$ 1 ton acre^{-1} in.$^{-1}$

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9 July) but not after the fifth, sixth and seventh cuts (11 August, 9 September and 3 October). In 1953 the basal dressing was applied on 17 March, and nitrogen dressings, N_1 and N_2, applied on 27 March. As before, 'Nitro-Chalk' was given after the first six cuts (13 May, 8 June, 3 July, 4 August, 24 August and 16 September). The final cut was on 29 October, and the site was ploughed on 24 November.

There was randomisation of treatments in 1951, but no change was made in 1952 or 1953, either in fertiliser treatment or in watering treatment: thus treatments called ON_1, or CN_2, refer to the same plots (and plants) throughout the three years. Yields were estimated from fresh weight, measured on the plots, and dry matter contents determined on samples. After plentiful rain or irrigation the dry matter content was about 20%: after drought and no irrigation it was about 35%. From small samples, *rough* estimates were made of the grass and clover contents, too crude for safe use in quantitative analysis, but useful in providing numbers to match visual impressions of sward composition. This, summarised as the ratio in annual totals (Table 1) varied throughout each summer on a given plot, and was clearly changed by nitrogen treatment (more N, less clover) and by watering treatment (more water, more clover). Because of the seasonal changes and the interactions of treatments it was thought—quite wrongly, as it happened—that a mixed ley of this kind would not be amenable to any profitable attempt to extract crop/weather relationships. Accordingly, the site was ploughed, and re-seeded in April 1954 with a pure stand of cocksfoot (see next section). This gave some very valuable relationships, and the doubts of 1953 were removed when it was found (Penman, 1967–68) that the same analytical treatment could be applied to the results of Stiles and Williams (1965) who had done almost exactly the same experiment on irrigation of a mixture of ryegrass and white clover at the Grassland Research Institute. The inference—steadily becoming more confident as experience accumulates—is that within a given system of well-managed farming, the composition of a crop does not greatly affect the total yield of dry matter, and it is not important whether the division is, as in a ley, between species, or, as in a monoculture, between components, e.g. roots and tops, or grain and straw. (Sugar beet is a notable exception: it seems to produce more dry matter for a given radiation income than any other crop in the world.)

For the present survey it has seemed worthwhile to re-examine the results for 1951–53 in the same way as was done for the cocksfoot 1954–59, so providing something new, avoiding repetition, illustrating the degree of success attainable in handling equation (4) diagrammatically, and, incidentally, raising the same scientific problems as emerged from all the other years and crops.

As part of the general survey for leys the results appear at the top of Table 2. Here the yield for Y_I is that from the plots receiving most water: in one out of the six responses given it was not the maximum yield. For the detail leading to these annual totals and responses it is necessary to know a little about the history of management and weather.

1951. The engineering was not completed soon enough, and the first irrigation was applied later than desired. Some was applied before the first cut (there was no nitrogen discrimination at this stage) and more before the second cut on the *C* plots. These then had no more (*A* and *B* had a little) and it is best to compare only the *O* and *C* plots for 1951. The cumulative yields appear on Fig. 2a plotted against E_T from a zero time taken as at the first cut, when yields for N_1 and N_2 were the same—at zero nitrogen dressing. The starting point for the lines drawn is at the time of the first irrigation when the unknown amount of growth would be the same for all plots, irrespective of later treatments.

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1952. There was no need for irrigation until after the second cut, so the first two sets of points on Fig. 2b represent replicate treatments. After the second cut there was a dry period of eight weeks, and then enough rain to satisfy water need. The zero time is the date of the last cut in 1951.

1953. The first nitrogen was applied before the first cut, and the first irrigation between the first and second cuts. After several weeks of need, the summer weather was broken by three weeks of unusually heavy rain after mid-June. For the *C* plots this gave a total of 'estimated drainage' of 14 cm up to the time of the last cut, nearly half of it between cuts 3 and 5. The zero time is near the date of the last cut in 1953.

The weather distribution in 1951 was fortunate, in that all the irrigation need came before the crop was established, and the important aspects of the results can be picked out without any knowledge of maximum or limiting deficits. From the second cut onward, the sets of three points are colinear, and within each pair the lines are parallel. The

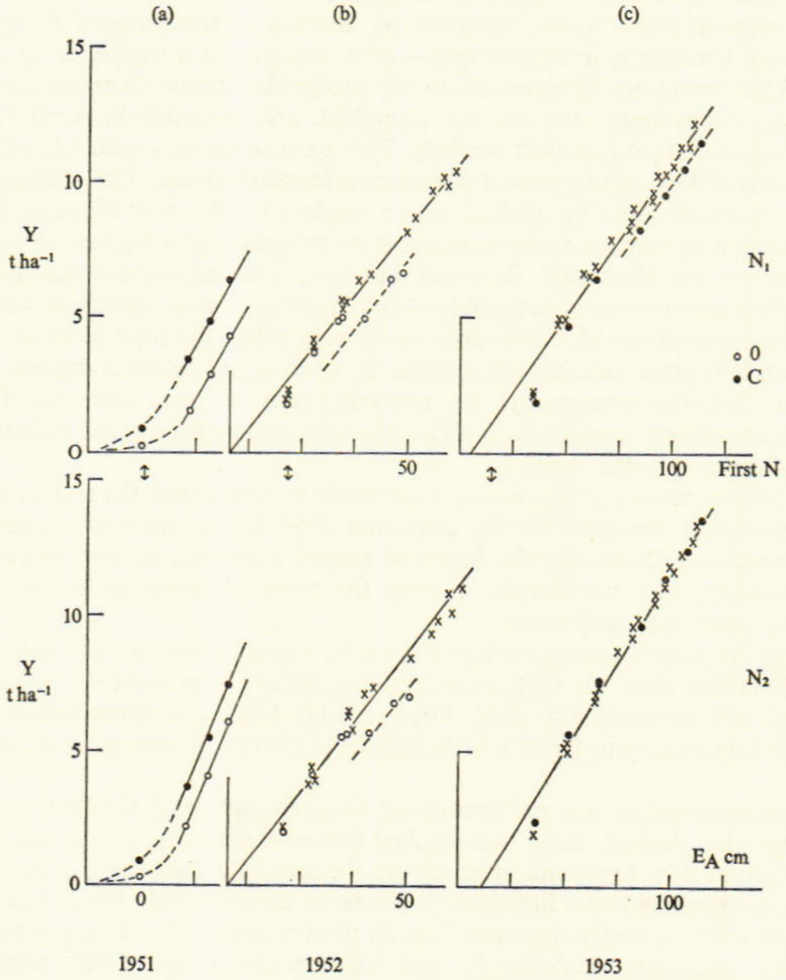

FIG. 2. Cumulative growth curves: grass/clover 1951–53. Points for control plots (*O*) and most-irrigated plots (*C*) are distinguished only where they have a special interest. The abscissa is accumulated *active* evaporation, estimated from the date of the first cut in 1951, and using $D_l = 2{\cdot}5$ cm for N_1, and $D_l = 3{\cdot}8$ cm for N_2. ($N_2 = 2 \times N_1$.)

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slopes are $k_1 = 0{\cdot}38$ t ha^{-1} cm^{-1} for N_1, and $k_2 = 0{\cdot}48$ t ha^{-1} cm^{-1} for N_2, both very large values indicating that the crop grew rapidly and made very efficient use of solar radiation. The irrigation response is revealed in two ways. First, the vertical separation shows the increase in yield produced by irrigation, and at the last cut of all this is $Y_I - Y_O$ of Table 2. Divided by the amount applied ($I_c = 8{\cdot}9$ cm), the responses of 0·23 and 0·16 t ha^{-1} cm^{-1}, for N_1 and N_2 respectively, are much smaller than the values for k_1 and k_2. Second, the horizontal separation represents a time benefit in getting the crop established. In E_T units, the values are about 6 cm for N_1 and about 3 cm for N_2: between the second and third cuts these intervals represent about 22 and 11 days. Qualitatively, the results are coherent. The greater horizontal spacing for N_1 implies greater sensitivity to soil moisture deficit, and hence greater response to irrigation, but quantitatively the size of the difference is surprising. There was *no* nitrogen applied until after the first cut, and yet by the time of the second cut the differential effect of two rates was fully established, over a period in which there was enough rain to get the unirrigated plots fully established. Were it worth seeking here, the explanation might be found in the grass/clover ratios at the second cut. They were: ON_1, 0·9; CN_1, 0·5; ON_2, 5·5; and CN_2, 0·8. As already noted, these ratios are very approximate, but, crude as they are, they indicate that the clover was dominant on three of the treatments and almost absent from the fourth (ON_2). The 'greater sensitivity to soil moisture deficit' may be that clover is more sensitive than grass.

The first cut in 1952 was for equal treatments since early September 1951, with the yields from the N_2 plots only a little greater than those from the N_1 plots (averages: N_1, 1·97; N_2, 2·14 t ha^{-1}) (Fig. 2b). Throughout the summer the ratio of growth rates never really exceeded this ratio (final values of Y_I: N_1, 10·4; N_2, 11·0 t ha^{-1}), and because the differential response was small it is unlikely that the absolute effects were very great. When Y was plotted against $E_T - D_m$ there was evidence of coherence in B and C results ($I_B = 8{\cdot}6$ cm; $I_C = 13{\cdot}0$ cm) with A and O results clearly anomalous. The coherence was improved by using as limiting deficits, 2·5 cm for N_1, and 3·8 cm for N_2. In plotting, for Fig. 2b, the last three points for A treatment were omitted (for clarity), and the last three for O treatment were not put in until the straight lines had been fitted to the remaining 22 points. Except for the values at the first cut, the straight lines drawn fit the observations very well, and, extrapolated back to $Y = 0$, the apparent zero time coincides with the date of the last cut in the previous year. The deviation of the first cut values always occurs—it is obvious again for 1953—but it is not an effect of irrigation.

The slopes of the lines are: N_1, 0·25 t ha^{-1} cm^{-1}; N_2, 0·26 t ha^{-1} cm^{-1}, as the maximum possible response to irrigation: the real responses (Tables 1 and 2) are greater. The beginnings of an explanation of this apparent absurdity can be seen on the diagram. From cut 3 to cut 5 the growth on the O plots was barely measurable, i.e. there was no response to the rain that fell during the period (8 cm in 56 days). From cut 5 on, growth was resumed, and at the same rate as the well watered B and C plots. For the N_1 line, with slope 0·25 t ha^{-1} cm^{-1}, the displacement of the control plot results is 1·3 t ha^{-1}, corresponding to an unused amount of rainfall of 5 cm. This is another benefit from irrigation: for a crop that would otherwise go senescent in a period of near drought, irrigation not only produces its own response to water paid for, but also keeps the crop in a state that it can respond to rain, which is free.

The important change in management in 1953 was that nitrogen dressings were applied in spring, before the first cut, and after six of the seven cuts, equal in amount to the total applied in the previous two years. The processing of results was as for 1952, with the same limiting deficits (N_1, 2·5; N_2, 3·8 cm) but the lines were drawn through the points

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before plotting the results for the fully watered C treatment. The reason—now considered unjustified—was a suspicion that the small yields on the C plots were caused by leaching of nutrients during the wet period between cuts three and five. The leaching idea was abandoned, first because there is no hint of it in the N_2 results, and, second, because the CN_1 results lie below the line from the second cut onward: a poor first or second yield, or a faulty measurement of either, would be carried forward into all later totals. The final four points for CN_1 lie on a line parallel to the full line, with slope $k_1 = 0{\cdot}28$ t ha^{-1} cm^{-1}. For N_2, $k_2 = 0{\cdot}32$ t ha^{-1} cm^{-1}, and here the ratio k_2/k_1 is nearer the value it had in 1951 (Table 1). The intercepts on the axis at $Y = 0$ are near the zero time corresponding to the date of the last cut in the previous year: they are also near the date of the first application of nitrogen. Farm practice is to apply spring dressings of nitrogen when spring growth is seen to have started, so this second near coincidence may be more meaningful than the first.

General

Grass, 1954 onward. Table 2 gives yields without irrigation (Y_O) and the responses to irrigation (Y_I–Y_O) for 12 years. For all entries, Y_I is the yield from C plots that had

TABLE 2

Response of leys to irrigation, 1951–65

Dry matter, t ha^{-1}

$N_1 = 0{\cdot}15$, $N_2 = 0{\cdot}30$, $N_4 = 0{\cdot}60$ cwt acre^{-1} N per application

Year	I cm	Y_O N_1	Y_O N_2	Y_O N_4	$Y_I - Y_O$ N_1	$Y_I - Y_O$ N_2	$Y_I - Y_O$ N_4	$(Y_I - Y_O)/I$ N_1	$(Y_I - Y_O)/I$ N_2	$(Y_I - Y_O)/I$ N_4
					Mixture: 2 grasses, 2 clovers					
1951	8·9	4·3	6·0	—	2·1	1·4	—	0·23	0·16	—
1952	13·0	6·7	7·0	—	3·7	4·0	—	0·29	0·31	—
1953	14·2	10·3	11·8	—	1·2	1·7	—	0·08	0·13	—
					New crop: S 37 Cocksfoot					
1954	7·4	4·0	6·5	—	0·0	−0·1	—	0·0	0·0	—
1955	19·6	4·6	6·8	—	3·3	3·4	—	0·17	0·18	—
1956	9·9	7·0	10·2	—	2·0	2·3	—	0·21	0·23	—
1957	13·7	—	7·9	10·5	—	2·3	2·1	—	0·17	0·16
1958	10·9	—	9·2	11·5	—	0·8	0·1	—	0·07	0·01
1959	17·3	—	3·4	4·3	—	4·2	5·6	—	0·24	0·32
					New crop: S 22 Italian ryegrass					
1960	8·4	—	10·5	12·0	—	2·1	3·1	—	0·25	0·35
1961	15·2	—	5·6	5·7	—	3·1	6·5	—	0·20	0·43
1962–64					Lucerne (Table 3)					
					New crop: S 22					
1965	3·8	—	—	12·0	—	—	0·0	—	—	0·0

most water applied. There were changes in the intensity of nitrogen dressings, and in the basic fertiliser too, but these will be noted as they become relevant. In nine of the 12 years the response was at least half-a-ton per acre of dry matter, and in some years very much better. The three years of zero response—1954, 1958, and 1965—differed in rainfall distribution. In both 1954 and 1958 there were intermittent relatively dry periods, and, with no long-range weather forecast as a guide, each dry period was treated as the

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beginning of real summer weather. Invariably application of irrigation was followed by rain: by the end of 1958 the *C* plots had received more irrigation and rain than they could hold but the estimated leaching seems to have done no harm to the absolute yield, but may have decreased the response to nitrogen a little. During 1965 the summer rain was very uniformly distributed and there were only two occasions when irrigation was called for—but some response was expected. One factor that may have contributed to failure was the intrusion of volunteer lucerne as a weed: by the end of the summer the infestation was too severe to justify continued cropping into 1966, and beyond, as planned, and the experiment was ended.

Cocksfoot, 1954–59. The crop was sown on 7 April 1954 in a dry period, and *all* plots were irrigated early in May to get it established. Basal fertiliser, and nitrogen had been applied the day before sowing (P_2O_5, 0·6; K_2O, 1·2; N_1 and N_2, 0·15 and 0·30 cwt acre^{-1}). There were six cuts in 1954, and N_1 and N_2 were applied after each cut except the last (4 November). For 1955 (seven cuts) and 1956 (six cuts) there were the same spring dressings and N applications after cutting. A change was made in 1957. The half plots previously at rate N_1 were now given four times as much (labelled N_4): the N_2

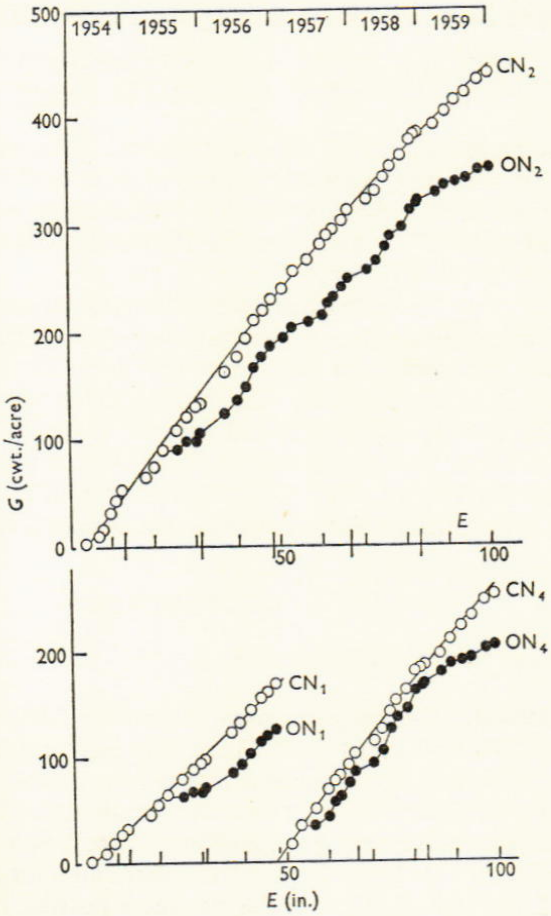

FIG. 3. Cumulative growth curves: S 37 Cocksfoot 1954–59. The abscissa is accumulated potential evaporation. (Note the units.) From: *J. Agric. Sci.* (1962), **58**. (Cambridge U.P.)

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plots continued as before. Yields had been good, and it was suspected that the crop might be exhausting potash reserves, so, in 1958 and 1959, supplementary potash was added to 6/12 plots. There was weed invasion in the sixth summer and the experiment was ended after the cut on 9 September. The unirrigated plots were very dry and hard: they were irrigated on 14 September (2 cm) and this made ploughing possible a week later (another benefit from irrigation).

Details of analysis are in II and only a few need repetition. Figure 3 reproduces Fig. 2 of II, the top half showing the total growth for CN_2 and ON_2 plots, over a period of six summers and five winters, plotted against accumulated potential transpiration. The first obvious result is that the average gain from irrigation was near 25%. The line drawn, obviously a good general fit, has a slight curvature towards the end (effect of weeds?). For any summer the line somewhat distorts trends, particularly in the first year. Using only the results from the *C* plots, the individual values of k_2 are:

1954, 0·40; 1955, 0·28; 1956, 0·33;
1957, 0·21; 1958, 0·33; 1959, 0·21 t ha^{-1} cm^{-1}

The full analysis, applied to all treatments, was given (Fig. 3 in II) for two years only, using values of limiting deficit: N_1, $D_l = 2{\cdot}5$ cm; N_2, $D_l = 3{\cdot}8$ cm; N_4, $D_l = 5{\cdot}1$ cm. (These have illusory precision—read them as 1, 1½ and 2 inches.) The values of k derived were:

$$1955,\quad k_1 = 0{\cdot}20;\quad k_2 = 0{\cdot}27 \text{ t ha}^{-1}\text{ cm}^{-1}$$
$$1957,\quad k_4 = 0{\cdot}28;\quad k_2 = 0{\cdot}24 \text{ t ha}^{-1}\text{ cm}^{-1}$$

The lines then drawn, representing $Y = kE_A$, repeated the behaviour of Fig. 2: for 1957 the intercepts at $Y = 0$ were very nearly the same and close to the origin at the time of the last cut in 1956 (as for 1952 and 1951); for 1955 the intercepts were the same for both N_1 and N_2, but to the right of the origin (as for 1953 and 1952) and very close to the time of the spring application of nitrogen.

There was a similar contemporary experiment at the Grassland Research Institute, Hurley (Stiles & Williams, 1965). A ryegrass/white clover sward, established in 1951 came into an irrigation experiment for four years 1956 to 1959. One of the treatments was the same as the Woburn *C* treatment, and, by chance, the nitrogen treatments were the same as the N_1, N_2 and N_4 at Woburn, and used the same material. There was also a zero treatment, N_0. From weather records at Kew Observatory values of E_T were calculated for the period (Penman, 1967–68), and used to plot total yield against total E_T. The result was a set of straight lines similar to that of Fig. 3 and the general slopes were:

$$k_0 = 0{\cdot}18;\quad k_1 = 0{\cdot}20;$$
$$k_2 = 0{\cdot}24;\quad k_4 = 0{\cdot}30 \text{ t ha}^{-1}\text{ cm}^{-1}.$$

The Woburn and Hurley results agree very well.

Italian ryegrass, 1960–61. The crop was sown in October 1959, and a basal dressing of N, P and K was applied on 1 April 1960. There were eight cuts to 8 November, and dressings N_2 and N_4 (as before) were applied after each cut except the last, and muriate of potash was applied to half plots after the first and fourth cuts. There was an excellent yield from the control plots and a very good response to irrigation. Simple trial showed that $D_l = 5$ cm was adequate for both nitrogen treatments, and, for the larger K dressing represented in Table 2, the derived values of the maximum possible response to irrigation were:

$$k_2 = 0{\cdot}34;\quad k_4 = 0{\cdot}40 \text{ t ha}^{-1}$$

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The measured responses, in the table, are smaller, as expected. There was some evidence of a rather complex interaction between K treatment and response to irrigation, discussed, but not clearly resolved, in Paper V.

In 1961 the best yield was less than was expected, perhaps because of a strong invasion of *Poa annua* that started at the beginning of July. It was killed by drought on the control plots, but persisted on the watered plots, though very little appeared in the cut grass. The slope of the line $Y = kE_A$ for the larger nitrogen and potash dressings was $k_4 = 0{\cdot}27$ t ha^{-1} cm^{-1}. The measured value of $(Y_I - Y_O)/I$ was 0·43 t ha^{-1} cm^{-1}.

Here is another example of the enhanced benefit from irrigation, because unwatered plots could not exploit rain.

Because of the weeds, the plots were ploughed up, and, after three years under lucerne, another grass crop was sown in 1965.

Italian ryegrass, 1965. The experience with fertilisers in the earlier experiments on this particular soil suggested that a change in practice was desirable to maintain the large yields obtained by irrigation. In the event it was not given a thorough test, but the applications, for 1965, were: Basal, applied immediately before sowing, March 1965: P (0·6 cwt acre^{-1} P_2O_5); NK compound at two rates (0·5 or 1·0 cwt acre^{-1} N; 0·5 or 1·0 cwt acre^{-1} K_2O). There were five cuts, and the NK compound, at the two rates, was applied after each cut except the last.

As already noted, the small amount of irrigation had no effect, there was no weather problem in getting the crop established, the yield was good, and from the slope of the line $Y = kE_T$ the value of k was 0·46 t ha^{-1} cm^{-1}, representing very efficient fixation of solar radiation.

Lucerne 1962–64 (Table 3). The lucerne came in the ley sequence on series IV (see Table 2), after ryegrass. The fertiliser treatments balanced those given to the grass. They were:

TABLE 3

Response of legumes to irrigation

Dry matter, t ha^{-1}

Lucerne, 1962–64

		Y_O				Y_I			
		K₁		K₂		K₁		K₂	
Year	I cm	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1
1962	8·9	5·73	5·87	5·78	6·09	6·23	6·59	7·25	6·90
Response t ha^{-1} cm^{-1}						0·06	0·08	0·16	0·09
1963	5·1 early 3·2 late 8·3 early and late	No response				Average yield = 7·9 t ha^{-1}			
1964	1·3 early 2·5 late 6·4 early and late	No response				Average yield = 9·5 t ha^{-1}			

Clover, 1963–65

Year	I cm	Y_O	Y_I	Response t ha^{-1} cm^{-1}	Notes
1963	7·0	2·13	3·23	0·16	Crimson C. 1 cut only
1964	11·4	6·08	8·78	0·24	Dorset Marl. 3 cuts
1965	3·8	8·52	8·54	0·00	Dorset Marl. 3 cuts

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P_2O_5 at 0·6 cwt acre^{-1} on all plots; $N_0 = 0{\cdot}0$ and $N_1 = 0{\cdot}3$ cwt acre^{-1} of N as 'Nitro-Chalk'; $K_1 = 0{\cdot}3$, and $K_2 = 0{\cdot}9$ cwt acre^{-1} of K_2O as muriate of potash. Fertiliser was applied two weeks before drilling the seed, and the NK treatments were repeated after each cut, including the last on 3 October 1962. In 1963 and 1964 there was spring application of NPK, and only K dressings after cutting.

As for the first ley, in 1951, all the irrigation in 1962 was applied before the first cut, and on all treatments the benefit was clearly established by the time of the first cut, with K_2 plots just a little better than K_1. Later behaviour was different: for three treatments the value of $Y_I - Y_0$ decreased at both the second and third cuts, to about half of its value at the first cut. The exception was the N_0K_2 treatment, which maintained its early response.

The yield gap established in 1962 was maintained in 1963 and 1964 (no response to irrigation), and plotting of total yield against total E_T (V; Fig. 6) gave three groups of 3, 3 and 4 points, each group fairly fitted by a straight line, the three lines very nearly parallel with slope 0·26 t ha^{-1} cm^{-1}, but not colinear. The obvious winter gaps correspond to a period without growth from the end of November to mid-March. A rough estimate of limiting deficit for the established crop was: $D_l \simeq 11$ cm. This confirms world experience, that lucerne is a deep-rooting crop and can survive drought better than any other fodder crop.

Clover*, *1963–65 (Table 3). The clover was grown as part of a three-course rotation. In each year it followed barley, in 1963 as a newly drilled crop (April), and in 1964 and 1965 as crops undersown in preceding barley crops selectively irrigated.

As for the 1951 ley and the 1962 lucerne, irrigation of the Crimson Clover in 1963 helped establishment, there was a good response at the first cut, and then no more: the experiment was abandoned. The combination of sunshine and irrigation increased inter-node spacing so much that the cutting completely defoliated the crop, and there was no significant recovery, even with irrigation.

The Dorset Marl had basal PK fertiliser applied in February 1964 and 1965, there were four irrigation treatments and these were distributed so that the plots watered in the barley year got least in the clover year. There was no doubt about the excellence of response in 1964, but there is some confusion in results for 1965. The balancing of watering treatments between 1964 and 1965 meant that the least watered plots in 1965 had a better start because they were irrigated in 1964.

The results for 1964 and 1965 gave 24 yields (three cuts, four watering treatments, two years), and plotting Y against $E_T - D_m$ gave a well distributed set of points lying closely about a straight line of slope $k = 0{\cdot}23$ t ha^{-1} cm^{-1}—the expected maximum possible response to irrigation. (The two points for crimson clover conformed well.) This is the same as the measured response in 1964 (Table 3), and implies that the limiting deficit for clover is small, and that there was a period during 1964 in which the unwatered plots were not making full use of the rain they received. A provisional value of D_l is 2·5 cm, but it may be smaller.

Crops grown in rotation

Introduction. Formal analysis is more difficult for annual crops: there is only one yield per treatment per year, the yield may not be the total botanical yield, and there is uncertainty about the length of the growing season (particularly the end—harvest may be delayed). Nevertheless it seemed worthwhile attempting to fit the standard equation

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$Y = k(E_T - D_m + D_l)$ to results, circumventing the uncertainty in E_T in various ways to reach acceptable estimates of D_l, the limiting deficit needed to guide good irrigation practice, and of k, the maximum possible response to irrigation, either for the whole crop, or for the part of economic value.

Potatoes

Early potatoes, 1951–53, 1960–62 (Table 4). These were not truly early potatoes. Planting dates ranged from 13 March to 25 April, and harvest from 10 to 31 July. In the fertiliser treatments there was basic P and K (more in 1960–62 than in 1951–53), and two intensities of nitrogen ($N_1 = 0{\cdot}5$, $N_2 = 1{\cdot}0$, 1951–53; $N_1 = 0{\cdot}6$, $N_2 = 1{\cdot}2$ cwt acre^{-1}, 1960–62). There were only two watering treatments (O and C) during 1960–62: another management variant was imposed, in a comparison of normal cultivation with weed control by chemical means. The result was not successful; all yields and responses were decreased by about one-third. Results in Table 4 are for normal cultivation.

TABLE 4

Response of potatoes to irrigation

Tubers as harvested, t ha^{-1}

		Y_O		$Y_I - Y_O$		$(Y_I - Y_O)/I$		Approx. $4k$	
Year	I cm	N_1	N_2	N_1	N_2	N_1	N_2	N_1	N_2
			Early—(1) Ulster Chieftain, 1951, 1952, 1953						
1951	5·6	9·3	9·5	9·5	11·4	1·7	2·0		
1952	6·9	14·7	15·2	9·1	11·5	1·3	1·7	1·8	2·0
1953	5·1	24·5	29·5	4·9	6·6	1·0	1·3		
			(2) Arran Pilot, 1960, 1961, 1962						
1960	3·8	22·7	26·0	4·5	6·5	1·2	1·7		
1961	10·2	14·6	17·2	18·7	20·2	1·8	2·0	1·8	2·1
1962	7·6	7·2	7·0	6·0	8·5	0·8	1·1		
			Maincrop—(1) Majestic, 1954, 1955, 1956						
1954	5·6	34·5	44·0	−2·0	−2·2	−0·4	−0·4		
1955	16·0	26·5	28·0	20·1	15·3	1·3	1·6	1·8	2·0
1956	1·3	34·8	38·3	1·5	1·2	1·2	0·9		

(2) Maris Piper and Pentland Dell, 1966 onward, on the same sites

		No fumigant				Fumigant				
		Cysts		No cysts		Cysts		No cysts		
Year	I cm	Y_O	Y_I	Y_O	Y_I	Y_O	Y_I	Y_O	Y_I	General response
1966	7·6	27·4	22·0	44·5	35·0	38·2	33·6	46·4	42·5	−
1967	10·8	8·9	10·5	22·5	22·3	20·2	28·1	31·0	37·7	+
1968	4 or 6	19		26		30		33		0
1969	6·5	6	9	←worst		best→		42	50	+

Responses were good in all six years, yields being doubled in 1951, 1961 and 1962, but the last result must be received with caution. The seed tubers were damaged by frost before planting, growth was patchy, and absolute yields were poor. Some of the measured responses are very close to the theoretical maximum, again indicating that the value of D_l is small, and that in 1951, and 1961, and probably in 1952 and 1960 the secondary benefit of irrigation was operative: it kept the crop in a state to exploit all the rain that fell.

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Majestic*, *1954–56 (Table 4). The same fertiliser treatments as for 1951–53 were imposed on a basal dung dressing of 15 tons acre^{-1}. There were two wet years in three, giving a small negative response in 1954 (wet), a very big response in 1955 (dry), and a small response in 1956 (wet). The negative response is considered later.

In analysis of these results and those for 1951–53 it was found—and noted as fortuitous at the time—that all could be fitted by the same straight lines of $Y = C(E_T - D_m + D_l)$ with two values of C_1 and C_2 corresponding to N_1 and N_2, using the same value of $D_l = 2{\cdot}5$ cm for both varieties. These slopes are given under 'Approx. $4k$' in Table 4, and, if the implicit assumption is accepted, then the slopes for dry matter production are: N_1, $k_1 = 0{\cdot}45$; N_2, $k_2 = 0{\cdot}50$ t ha^{-1} cm^{-1}, about the same as for a fully established grass ley in its first year.

Main crop*, *1966 onward (Table 4). After 15 years under ley, Series IV was only slightly infested with potato cyst-nematode, whereas Series I had carried several potato crops, and some plots were heavily infested. The sites are now used for a long-term experiment in nematology, comparing resistant and susceptible varieties of potato, in succession and alternating, with and without soil fumigation, and with and without irrigation. An undistorted summary is unattainable, but the selected material in the fourth section of Table 4 may not be too misleading. For 1966–68 average yields of the two varieties show an unexpected negative response to irrigation in 1966, a good response in 1967, but somewhat smaller than expected, and no response in 1968, as expected (only average yields are given). For 1969 the best (Maris Piper, the resistant variety on fumigated cleaner plots) and worst (Pentland Dell, non-resistant on non-fumigated infested plots) yields are given. The best yields, and the response to irrigation, are about the same as for Majestic potatoes in 1955.

The behaviour in 1966 repeated that of the main-crop in 1954, but with bigger negative responses. The explanation offered is that in 1966 the combination of early watering and rain produced estimated drainage through the irrigated plots and none through the control plots, in amount 2·5 cm by the end of June, 3·7 cm by the end of August, and 5·3 cm by harvest time. The effect was about equivalent to halving the nitrogen dressing (1·2 cwt acre^{-1} N in basal NPK). The same effect probably occurred in 1954: colour contrasts in foliage early in July 1954 provoked the query 'Leaching?'. The early leaching may be the more important.

Sugar beet. Table 5 includes results from experiments, 1948–50, on commercial farms (Penman, 1952) where two farmers co-operated with the British Sugar Beet Research and Education Committee: at least one treatment was based on weather records collected on or near the site, and this provides the entry in the table.

Management was very much the same throughout. There was basal PK, sometimes agricultural salt, and two intensities of nitrogen fertiliser, with $N_2 = 2 \times N_1$. Values were: 1948–50, $N_1 = 0{\cdot}4$; 1951–56, $N_1 = 0{\cdot}4$; 1957–59, $N_1 = 0{\cdot}6$; 1963–65, $N_1 = 0{\cdot}75$ cwt acre^{-1}.

During the 15 years there were good to excellent responses in six, the outstanding returns coming in years of late summer drought (1949, 1955, 1959 and 1964). There were five years in which there were small negative responses on the plots that got most water, perhaps because of leaching, but the evidence is not conclusive, and there may be some other factor to look for. The results given are for sugar yields: they fluctuate greatly from year to year, and the total botanical yield probably changed as irregularly, so there is little hope of any successful synthesis that will give the important parameters

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TABLE 5

Response of sugar beet to irrigation

Sugar, t ha^{-1}

Year	I cm	Y_O N$_1$	Y_O N$_2$	$Y_I - Y_O$ N$_1$	$Y_I - Y_O$ N$_2$	Selected $(Y_I - Y_O)/I$ N$_1$	Selected $(Y_I - Y_O)/I$ N$_2$
			Milford (Surrey)				
1948	6·6	—	8·4	—	0·1	—	—
1949	21·0	4·5	4·4	1·0	1·2	0·05	0·06
			Kesgrave (Suffolk)				
1949	14·8	3·8	3·9	3·0	2·4	0·20	0·16
1950	10·2	6·5	6·9	1·8	1·1	0·18	0·11
			Woburn (Beds.)				
1951	8·6	5·5	7·1	0·2	0·8	—	0·09
1952	14·2	5·9	7·0	1·4	0·5	0·10	—
1953	9·2	10·1	10·9	−0·1	−0·5	—	—
1954	3·3	5·2	5·9	0·0	0·0	—	—
1955	16·2	4·1	4·5	1·4	1·0	0·09	0·12
1956	3·6	7·5	8·4	−0·6	−0·2	—	—
1957	9·2	7·5	8·0	−0·5	−0·1	—	—
1958	4·6	5·2	6·2	−0·5	−0·5	—	—
1959	18·6	7·8	7·2	3·2	3·8	0·17	0·20
1963	8·3	7·8	8·0	0·1	0·8	—	0·10
1964	10·2	6·8	6·4	1·5	3·5	0·15	0·34
1965	3·8	8·1	8·1	−1·1	−0·3	—	—

in the total growth equation $Y = kE_A$. An attempt to do so on the results for 1963–65 (VI, Fig. 1a) gave a value of $k \simeq 1$ t ha^{-1} cm^{-1} for total dry matter, and if sugar represents 40% of total dry matter, then $k_S \simeq 0{\cdot}4$ t ha^{-1} cm^{-1}. The year to year variation can be eliminated by using the ratio S/S_m, where S_m is the maximum yield in the range of treatments, and S is the actual yield. This, plotted in Fig. 1b, in VI, for three years, is repeated here as Fig. 4, but now includes 12 years of Woburn results for all O, B and C plots. The few A plot values are omitted for clarity. The ordinate is the ratio S/S_m, as the average of the two nitrogen treatments. The abscissa is the maximum deficit, D_m, after the middle of July. The diagram is informative in several ways. Five of the O points lie below 90%, i.e. in five out of 12 years failure to irrigate decreased yield by more than 10%. Six of the B and C points are below 100%. (The lowest, at 0·91, is for 1965.) The roughly fitted line passes through $D_m \simeq 10$ cm at 100% and this offers a useful guide to irrigation management—keep the deficit at less than 10 cm from mid-July onward. The slope of the line is 0·045 cm^{-1}. For a good sugar yield of 8 t ha^{-1}, this would correspond to $k_S \simeq 0{\cdot}36$ t ha^{-1} cm^{-1}. This is a large value, confirming what is in Table 5: at its best the sugar production by a sugar beet crop is almost as good as the total dry matter production of a ley. The maximum values of $(Y_I - Y_O)/I$ anywhere in Table 5 are 0·20 (N$_1$, Kesgrave, 1949), 0·12 (N$_2$, Woburn, 1955), 0·17 and 0·20 (N$_1$ and N$_2$, Woburn, 1959), and 0·33 (N$_2$, Woburn, 1964).

In several years, early irrigation produced obvious response in top growth, but the benefit did not persist through to harvest. It is difficult to offer advice that will improve on the practice of one successful grower: give the crop a good soaking in mid-July (about 5 cm) and then no more unless the late summer is exceptionally dry.

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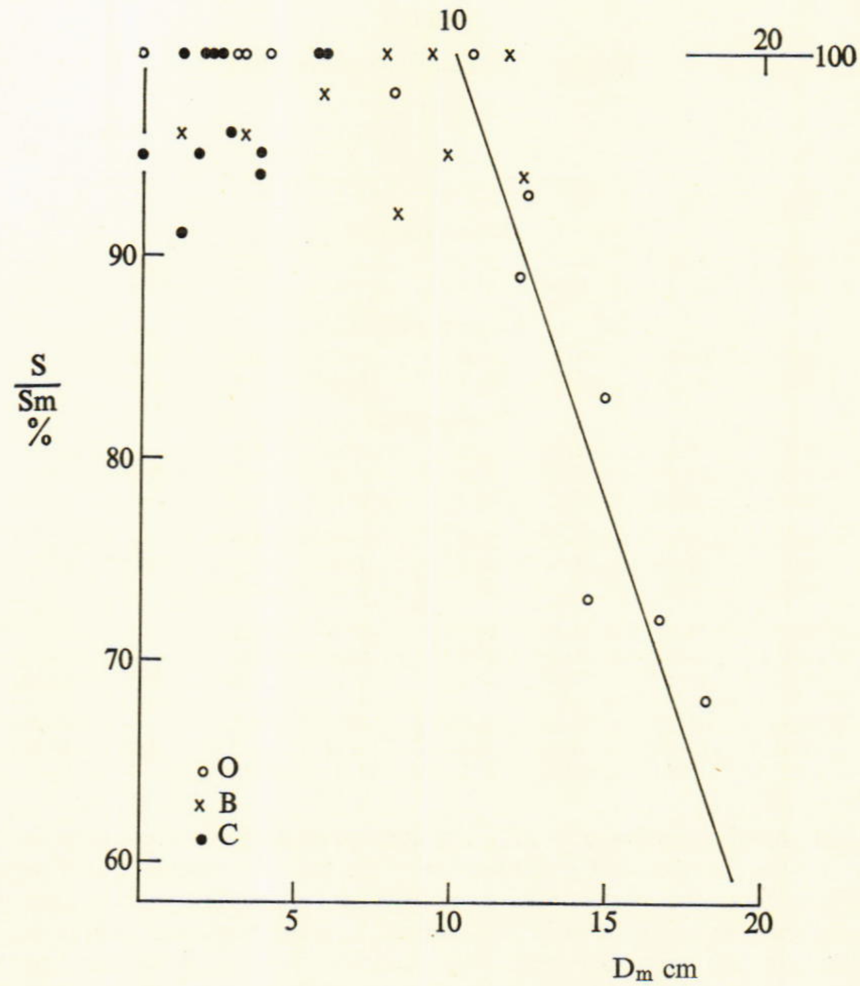

FIG. 4. Sugar yield (S) as a fraction of the best yield (S_m) plotted against maximum deficit after mid-July. 1951–59; 1963–65.

Barley (Table 6). The cereals have proved the least amenable to formal analysis, and even after 11 years of irrigation experiment on barley guidance on practice is based largely on impression. The results for 1968 in Table 6 are for interest only: an experiment on soil fumigation included irrigation as a variable, and there was some response where chloropicrin showed its efficiency as a nitrogen fertiliser.

For the ordinary experiments, 1951 onward, there was basal PK plus nitrogen at $N_1 = 0{\cdot}2$ and $N_2 = 0{\cdot}4$ cwt acre^{-1} up to 1956, and again 1960–62, but for 1963 and 1964 the rates were 0·3 and 0·6 cwt acre^{-1}. In the first two courses, barley came after potatoes in 1951 and after sugar beet in the other five years. In 1960 it came after a bean crop. In 1961, 1962 and 1963 the barley was in a sequence that started with early potatoes, half cultivated, half treated with weedicide, then some plots were drilled with trefoil, later ploughed in as green manure, and then came the barley. The results in Table 6 are for the sequence: potatoes cultivated, and no intervening trefoil. In 1963 and 1964 the barley was undersown with clover.

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TABLE 6

Response of barley to irrigation

Grain yield (dry matter), t ha^{-1}

Year	Variety	I cm	Y_O N_1	Y_O N_2	$Y_I - Y_O$ N_1	$Y_I - Y_O$ N_2	Selected $(Y_I - Y_O)/I$ N_1	Selected $(Y_I - Y_O)/I$ N_2
1951	Plumage Archer	8·1	2·71	3·76	0·91	0·39	0·11	—
1952	,, ,,	7·3	2·71	2·89	0·12	0·51	—	0·07
1953	,, ,,	2·0	2·96	3·74	−0·04	−0·14	—	−0·07
1954	Herta	4·6	3·91	4·60	0·22	−0·10	0·05	—
1955	,,	3·5	3·96	5·06	0·10	−0·14	—	—
1956	,,	6·6	3·08	3·90	0·56	0·44	0·08	0·07
1960	Proctor	5·1	2·12	2·73	0·35	0·39	0·07	0·08
1961	,,	8·2	2·71	3·27	0·09	0·21	—	—
1962	,,	8·9	2·05	2·60	0·84	1·07	0·09	0·12
1963	Proctor	7·0	1·78	2·72	0·45	0·76	0·06	0·11
1964	Maris Badger	5·1	3·00	3·90	0·24	0·03	0·05	—
			N_0	N_1	N_0	N_1		
1968	Maris Badger	3·2	1·08	2·93	−0·03	−0·04	No fumigant	
	,, ,,		3·04	3·33	0·29	0·14	Chloropicrin	

From the four years results for Proctor (and Maris Badger in 1964 conforms) it seems that the response of barley to irrigation can be interpreted if it is assumed to behave as a grass crop up to the time of ear emergence, i.e. the best grain yield will be achieved if the deficit is kept at less than 4 cm up to this stage: what happens after has little detectable effect. Visual checks on the results for the first six years show no extreme contradiction to this specification. For example, there was a good yield of Herta in 1955 when the condition was satisfied in both treatments, and, though there was severe drought afterward, there was no response to irrigation. (As a technical point, for both barley and wheat, irrigation was stopped when the farm manager considered that the risk of lodging was too great to accept.)

In general, responses were small, with erratic interactions of watering and nitrogen. Again as an impression, water and nitrogen seem to be interchangeable—but nitrogen always produces a response.

There is no information in Table 6 relevant to the other parts of the experiments of 1961–63. A quotation from Paper VI (p. 96) may suffice: 'Preceding management of the potato crop probably had no effect on the growth of the barley. Trefoil increased the yields, certainly at the smaller nitrogen dressing, probably at the larger one, halved the response to nitrogen, and may have increased the response to water.'

With great uncertainty, an approximate value of k_g is near 0·16 t ha^{-1} cm^{-1}, for the grain, for both nitrogen treatments.

Spring wheat (Table 7). During 1957–59 wheat came in a normal rotation, after sugar beet, and was given basal PK fertiliser plus nitrogen at intensity $N_1 = 0·4$ cwt acre^{-1} of N. Other rates, then and later, were N_2, N_3 (and N_4) at 2, 3 and (4) $\times$ N_1. The second group includes results for experiments in 1966 and 1967 on the dwarfing compound, CCC (Humphries, 1970). Four intensities of nitrogen fertiliser were used but as the fourth was rather far outside the specification of 'recommended best practice' results are given for three only. The values given are averages with and without CCC.

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TABLE 7

Response of spring wheat to irrigation

Grain yield (dry matter), t ha^{-1}

			Y_O			$Y_I - Y_O$			Selected $(Y_I - Y_O)/I$		
Year	Variety	I cm	N_1	N_2	N_3	N_1	N_2	N_3	N_1	N_2	N_3
1957	Peko	8·1	2·70	2·75	—	0·28	0·76	—	—	0·09	—
1958	,,	3·8	2·59	2·94	—	−0·14	−0·24	—	−0·04	−0·06	—
1959	,,	11·9	1·94	1·81	—	1·11	1·38	—	0·09	0·12	—
1965	Opal	3·8	3·48	4·04	3·90	0·21	0·42	0·21	0·06	0·11	0·06
1966	Kloka	7·6	2·68	4·08	4·31	0·58	0·44	1·13	0·08	0·06	0·15
1967	,,	10·2	3·79	5·02	4·56	0·37	0·45	1·18	—	0·04	0·12

Except in the wet summer of 1958, when there was a small negative response to a small amount of irrigation, spring wheat responded to irrigation, by more than 50% in 1959. There is much less evidence available than there is for barley, and generalisation is based on impression. Like barley, spring wheat should be treated as a grass until ear emergence: unlike barley, it seems to be somewhat sensitive to later deficit, and a guide to action would be: keep the deficit at less than 4 cm up to ear emergence and thereafter do not let it increase above $E_T/4$—measured from sowing date.

Analysis of the results gives a very tentative value of k_g for wheat as near 0·24 t ha^{-1} cm^{-1}, for the grain, for $N > N_1$: it is much less at the smallest nitrogen dressing, and apparently the wheat needed nitrogen at rate N_2 to be able to respond to irrigation.

Two general points in crop–weather relationships are worth noting here. First: spring wheat responds to water—positively—like any other grass crop, and a droughty summer is not the best for getting maximum yield out of a healthy crop. Second: the 1967 crop was healthy: there were straw yields too, and for the best nine plots the average total dry matter at harvest was 12 t ha^{-1}, even after losses during maturation. This is as good as is obtainable from a well managed ley or a very good potato crop.

Beans (Table 8). The first three years of spring beans had the fertiliser variant of dung at 12 tons acre^{-1} applied on half-plots in winter (D_1). The seed was drilled with a basic PK fertiliser. For the second three years the intention was to use winter beans, but drilling was not possible in autumn 1960, and the crop drilled in autumn 1961 failed. The 1968 crop had no PK, but was given nitro-chalk (four treatments) and a dwarfing compound (B-Nine, two treatments). The entries in Table 8 are for the zero treatments for N and B-Nine.

Analyses of the two sets of results (1957–59; 1960–68) give concordant values of limiting deficit near $D_l = 4$ cm, but the value of k_g, for grain, was near 0·14 for 1957–59, and 0·17 t ha^{-1} cm^{-1} for 1960–68: this is another way of indicating that yields were about 20% better in the second period.

Except in 1958 and 1968, when the summers were wet and little irrigation was applied, the responses were very good, and almost the same as the theoretical maxima inferred from the analysis. This confirms that the limiting deficit is indeed small, but if it is not to be made vanishingly small then in all five years of good response the irrigation was needed to keep the crop vigorous enough to respond to rain. Other crops have shown this susceptibility occasionally, but none so frequently, and the derived values of D_l may be over-estimates, and the conflict between real performance (as in Table 8) and predicted

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TABLE 8

Response of beans to irrigation

Grain yield (dry matter), t ha^{-1}

Year	Variety	I cm	Y_O D_0	Y_O D_1	$Y_I - Y_O$ D_0	$Y_I - Y_O$ D_1	$(Y_I - Y_O)/I$ D_0	$(Y_I - Y_O)/I$ D_1
1957	Spring tick	10·2	1·47	1·74	1·77	1·47	0·17	0·14
1958	,, ,,	2·5	1·91	1·79	0·09	0·05	0·04	0·02
1959	,, ,,	11·4	1·02	1·12	1·61	1·50	0·14	0·13
1960	Winter, RSQ	9·0	2·40	—	1·24	—	0·14	—
1961	Spring tick	11·4	1·41	—	1·65	—	0·14	—
1962	,, ,,	8·3	2·23	—	1·33	—	0·16	—
1968	Tarvin	3·3	2·95	—	0·16	—	0·05	—

maximum best becomes perhaps rather more severe. (At present, August 1970, at the end of a fairly dry summer, the bean crop is showing the same behaviour. On ordinary experiments, and on the unwatered control of the irrigation experiment, the crop is poor and only about 20 in. tall. The irrigated plants are about 40 in. tall.)

Discussion

(Table 9)

The value of successful irrigation is that it provides the water of a wet summer in the sunshine of a fine one. No one doubts that there is no need for it in wet summers such as 1954, 1958 and 1963, or that it could be beneficial in extremely dry summers such as 1955 (after June), 1959 and 1964, but in between there is uncertainty. Arbitrarily (i.e. based

TABLE 9

Fractional increases in yield (%) for maximum irrigation

Year	Year of 'need'?	Grass/ clover	Grass	Lucerne	Clover	Early potatoes	Maincrop potatoes	Sugar beet	Barley	Spring wheat	Beans
1951	+	23	—	—	—	120	—	11	10	—	—
1952	+	57	—	—	—	76	—	7	18	—	—
1953	0	14	—	—	—	22	—	−5	−4	—	—
1954	0	—	0	—	—	—	−5	0	−2	—	—
1955	+	—	50	—	—	—	90	45	−3	—	—
1956	0	—	22	—	—	—	3	−2	11	—	—
1957	+	—	29	—	—	—	—	−1	—	27	120
1958	0	—	9	—	—	—	—	−8	—	−8	5
1959	+	—	123	—	—	—	—	53	—	76	158
1960	0	—	18	—	—	25	—	—	14	—	52
1961	+	—	114	—	—	118	—	—	6	—	116
1962	0	—	—	26	—	122	—	—	41	—	60
1963	+	—	—	0	52	—	—	10	28	—	—
1964	+	—	—	0	44	—	—	55	1	—	—
1965	0	—	0	—	0	—	—	−4	—	10	—
1966	0	—	—	—	—	—	−12	—	—	11	—
1967	+	—	—	—	—	—	24	—	—	9	—
1968	0	—	—	—	—	—	10	—	−1	—	5
1969	+	—	—	—	—	—	19	—	—	—	—
Limiting deficit (in.)		1–1½	1–2	4	1	1	1	4	1½	1½	1½
Estimated k for whole crop t ha^{-1} cm^{-1}			0·3	0·3	0·2	0·5	0·5	1·0	0·3	0·4	0·3

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on judgement) *Technical Bulletin* No. 4 defined a year of irrigation need as one in which the excess of potential evaporation over rainfall is more than 3 in. for the period 1 April to 30 September. At Woburn this was expected to occur seven years in ten, but, as the second column of Table 9 shows, it happened only ten times in 19 years. This, though no more than an accepted variability in climatology, does mean that there have not been quite as many favourable proving years as expected. Even so, in 13 years at least one crop gave more than 20% increase in yield, in ten years at least one crop gave more than 50% increase, and in five years at least one crop yield was doubled. This is a fair enough summary of the field evidence, and has some legitimate propaganda value, but it is a little unfair technically. An alternative is: in five years at least one crop yield was halved because of lack of water, and one contributory factor was the failure of the crops to make full use of the rain they got. There is a need for another soil water parameter in growth studies, namely a deficit (or a water potential) within which the plant not only survives, but remains ready to respond to rain even when the growth rate is negligible or zero. It may be, as suggested in Paper V, that a promising index already exists (at least worth a trial) in the 'root constant' (Penman, 1949) introduced to account for the hydrology in terms of water balance, where growth is disregarded. At some stage, as the soil gets drier, the actual evaporation rate becomes smaller than the potential rate, and it may be at this stage, or a little beyond it, that the plant loses the ability to respond immediately to rain.

The conventional approach to responses, though it has been used in this survey, is not the best in water studies. For a given farming system there is a limit to the yield attainable when water supply is adequate, and it is the task of the remainder of agricultural research to raise this limit. Water cannot do so, but shortage of water can prevent a crop yield from reaching its optimum: part of the survey has been an attempt to show the scale of loss through the constant k. It has been called the 'maximum possible response to irrigation' (valuable if for no more than preventing too much being claimed for the technique—there's no magic or miracles in irrigation), but it is also a measure of the maximum possible loss in yield attributable to lack of water. With the very important qualification already sufficiently stressed (full use of rain), k as a measure of maximum disaster will always exaggerate because of the ability of the soil to store some water available for plant growth. Quantified through the limiting deficit, D_l, the value is not very different for all the crops in Table 9 (lucerne and sugar beet are the outstanding exceptions), at a value between 1 and 2 in. as rainfall equivalent. If this depends on the quantity of water held in the soil profile at low tension, then D_l will be bigger in soils heavier than the sandy Woburn loam: if—rather less likely, but possible—it depends on the depth of soil occupied by nutrients, then soil type may not be very important in determining the size of D_l. (N.A.A.S. experience on potatoes indicates that $D_l \simeq 1$ to $1\frac{1}{2}$ inches is best on a wide range of soils.)

The experiment had the advantage of first class management that got the best out of every crop. The values of k are a measure of this achievement, for, converted into dry matter equivalent of total botanical yield, they show no great spread (sugar beet excepted) about a general average near $k = 0{\cdot}3$ t ha^{-1} cm^{-1}: for a growing season with a total potential evaporation near 33 cm this corresponds to a total dry matter production near 10 t ha^{-1}, and an efficiency of fixation of solar radiation of about 80×10^{-4}. The efficiency of average British farming is near 35×10^{-4}. The point in these figures is that this efficiency (or the value of k) is a measure of the response to irrigation when irrigation is needed. The better the standard of farming, the greater is the return for added water.

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What happens to the water? Table 10 shows what might have occurred at Woburn, from April to November, with all quantities in centimetres per month. The first two lines give the rainfall and potential evaporation, and the third gives their monthly difference. The fourth line is a running total and represents the estimated soil moisture deficit at the end of each month: it reaches a maximum of 8 cm at the end of August (this would be D_m for the O treatment), and passes through zero in November to reach -5 cm at the end of the month (this would be 'estimated drainage' by that date). In line five is a possible C treatment, with irrigation amounts of 3 cm in both June and July, and after the obvious intermediate sixth, the seventh line gives the history of the managed deficit. The maximum is now only 3 cm, and it occurs at the end of June: the return to field capacity occurs in October (estimated drainage, 4 cm) and by the end of November the total estimated drainage is 11 cm, equal to that for the O treatment (5 cm) plus the added irrigation (6 cm).

TABLE 10

Idealised water-balance (cm per month)

		Month							
		April	May	June	July	Aug.	Sept.	Oct.	Nov.
	Rain R	5	5	5	7	6	5	7	8
O	Pot. evap. E_T	5	7	9	8	7	4	2	1
	$E_T - R$	0	2	4	1	1	-1	-5	-7
	Total $E_T - R = D$	0	2	6	7	**8**	7	2	(-5)
	Irrigation I	0	0	3	3	0	0	0	0
C	$E_T - (R + I)$	0	2	1	-2	1	-1	-5	-7
	Total $= D$	0	2	**3**	1	2	1	(-4)	(-11)

Accepting a very important unstated assumption, no irrigation water is consumed at Woburn. It starts in the Greensand aquifer under the plots and, after a complex route that makes it costly, it reaches the soil above the aquifer. Here it, or an equal amount, is stored until autumn rain is enough to wet the soil profile, and what was taken out from below in June and July is returned to source in October and early November, ahead of the main recharge through unirrigated areas. In the hydrological balance sheet for the area what was borrowed in summer is returned in autumn, and employed to grow a bigger crop in the interval. Suppose the crop to be grass with a limiting deficit of $D_l = 4$ cm, and consider growth from the end of March to the end of September. The value of E_T is 40 cm, and by the definition used the potential maximum yield is $40k$. For the O treatment the active evaporation ($E_A = E_T - D_m + D_l$) is $40 - 8 + 4 = 36$ cm and what would appear as Y_O in a table such as Table 2 is $Y_O = 36k$. For the C treatment D is always less than D_l and $E_A \equiv E_T = 40$ cm. Hence the corresponding entry for Y_I is $Y_I = 40k$. The derived measured response is then

$$(Y_I - Y_O)/I = (40k - 36k)/6 = 4k/6,$$

i.e. the measured response is less than the theoretical maximum by a factor 2/6, because 2 out of the 6 cm applied were not necessary: a total of 4 cm, applied either as two doses of 2 cm in June and July, or as a single dose in June—but *not* in July—would have served and given a full return equal to the maximum possible.

Here the assumption must be exposed. Does the diminished growth mean there is less water used? The best answer is: 'No—within limits,' so expressing the dominance of weather. The limits are imposed by plant and soil factors, and for the supposed crop

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and its seasonal water balance, as in Table 10, it is probable that the limit was reached at a maximum potential deficit of 8 cm. For a wetter summer the 'No' would be safe, and the hydrological inferences from Table 10 could be accepted. In a drier summer actual evaporation would be less than the potential, from the unwatered plots, for part of the time, because available water in the root zone was exhausted. Then the water balance in the upper part of Table 10 would be distorted in the sense that the actual maximum deficit would be less than the potential value (D_m), and autumn recharge of the aquifer would start sooner than predicted, and, relatively, the irrigation operation would seem somewhat disadvantageous.

The problem has some relevance to what farmers should pay for irrigation water, and a few more facts will be helpful. Current irrigation experiments at Rothamsted and Broom's Barn are beginning to provide these facts.

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