# Rothamsted Experimental Station Report for 1972 Part 2


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# Water Use by Farm Crops
## III. Bare Soil, Short Turf and Crops in Rotation, 1962 to 1967, 1971

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### Summary

Trusting the meter, all useful results from 1962 onward are set out, including some measurements (1962, 1963) confirming that evaporation from bare soil is greater in a wetter summer, plus an extended set of observations (1971) that showed actual evaporation to be the same as potential evaporation for a short turf surface (i.e. $\kappa = E/E_T \simeq 1{\cdot}0$). Except for potatoes and beans, monitoring to 90 cm was not enough, and at times the greater depth (to 150 cm) was barely adequate for cereals, sugar beet and kale: these crops show drying to at least 120 cm depth and often to 150 cm. On several occasions this deep drying persisted, without any obvious check, in periods when the upper soil layers showed a gain in water because of excess rain. In amount, the maximum net drying varied as the depth of action. For potatoes and beans it was about 30 to 50 mm before there was a check to rate of transpiration: for the other crops there was no check until 100 mm or more had been used. Usually, but not always, irrigated plots used more water than the controls (never less), the difference, $\Delta E$ being, in general $\ll I$, and this is the extra amount transferred to the atmosphere. The remainder, $I - \Delta E$ is a gain in the profile, held or already moved down as drainage, at the end of the season. Values of $\kappa$ were near 1·15 for hay grasses, winter wheat, spring barley, beans and potatoes, but spring wheat, sugar beet and kale gave values close to 1·3—surprisingly large. Nearly every year there was evidence of rain or irrigation water penetrating the soil profile without bringing any wetted layer to field capacity first, with possible consequences for movement of machinery and implements over the soil. Maintained wetting seemed to restore a 'field capacity', in that the water content 0 to 150 cm in February 1972 was the same as that measured at the wettest state in mid-June 1971, but it remains doubtful whether the concept is valid during the growing season, and some of the measured drying may be drainage.


### Introduction

The field use of the neutron moisture meter started in 1962, mainly to find out what it could do and how to use it. The source then, and until 1966, was Polonium 210/Berylium with a half-life of six months, and the first monitoring was to 90 cm depth in the profile. Experience led to use of a permanent source (1966 onward: Part I) frequent deeper monitoring, to 150 cm, and improvements in the counting circuit. Part I dealt exhaustively with the results for 1970 as a test of meter precision and accuracy; Part II considered, in almost the same detail, the field results for 1969 and 1968, exposing some other sources of uncertainty not detected in those for 1970. Here the results for 1962 to 1967 and 1971 are considered, using only those that have some possible value either in agronomy or agricultural meteorology. In the latter context, bare soil and short turf are 'farm crops'.

### Bare soil, 1962 and 1963 (Table 1)

While the soil surface is wet, the evaporation rate from bare soil is about the same as from a short crop, but it becomes very much smaller when the soil dries, usually within a



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few days in a summer period without rain. So the rate is strongly influenced by frequency of re-wetting, and hence there is a very strong correlation between evaporation and total rainfall (Penman & Schofield, 1941; Penman, 1940; Sahni, 1941). The summers of 1962 and 1963 show this effect very clearly. In 1962, the rainfall was 178 mm from 22 May to 13 September; in 1963, it was 246 mm from 7 June to 12 September. In 1962 the crop under test was winter wheat, but the depth of monitoring was too small to get reliable measurements of water use. It was, however, adequate for an area of bare soil, 7 × 7 m, in which two access tubes were inserted 5 m apart. First measurements were made on 22 May 1962 when the soil was a little above field capacity, i.e. water was still draining through the profile, and thereafter there were frequent monitorings until early October. At the last of these the strength of the radio-active source had fallen to half its initial value, and as the readings are suspect the season's survey will be curtailed in September. In general the agreements between duplicates was very good: because of this, for four periods, only one reading is used, first because on one occasion no readings were taken at one site, and second because a watering experiment near one site (to test another bit of equipment, irrelevant in the present context) distorted the readings for about three weeks. Though this could be classified as a 'dry' summer, there was enough rain to cause drainage through the bare soil, and the amounts cannot be estimated from the neutron meter measurements. Instead, the measured drainage from the nearby drain-gauge, 50 cm deep, was used. Both in 1962 and in 1963 study of the records suggested that the cultivated soil carrying the access tubes retained surplus water for several days longer than that of the drain-gauge, which has not been disturbed since 1870. There is no evidence to indicate any important difference in total discharge, and Table 1 assumes that there was none.

**TABLE 1(III)**

*Bare soil, 1962, 1963. Water balance (mm)*

| Period | $R$ | $\bar{D}$ | $R+\bar{D}$ | $d$* | $R+D-d$ | $\Sigma E_T$ |
|---|---|---|---|---|---|---|
| 1962 | | | | | | |
| 22/5–28/5 | 5 | 8 | 13 | 1 | 12 | 12 |
| 28/5–4/6 | 1 | 12 | 13 | 0 | 13 | 27 |
| 4/6–25/6 | 4 | 18 | 22 | — | 22 | 89 |
| 25/6–29/6 | 3 | −2 | 1 | — | 1 | 100 |
| 29/6–2/7 | 0 | 1 | 1 | — | 1 | 107 |
| 2/7–13/7 | 6 | 2 | 8 | — | 8 | 132 |
| 13/7–23/7 | 21 | −6 | 15 | — | 15 | 155 |
| 23/7–31/7 | 36 | −10 | 26 | 16 | 10 | 170 |
| 31/7–8/8 | 23 | −12 | 11 | 7 | 4 | 189 |
| 8/8–22/8 | 33 | 3 | 36 | 11 | 25 | 215 |
| 22/8–13/9 | 46 | −6 | 40 | 10 | 30 | 251 |
| 1963 | | | | | | |
| 7/6–12/6 | 47 | −18 | 29 | 22 | 7 | 14 |
| 12/6–19/6 | 12 | 1 | 13 | 0 | 13 | 31 |
| 19/6–24/6 | 3 | 2 | 5 | — | 5 | 45 |
| 24/6–17/7 | 68 | −6 | 62 | 25 | 37 | 94 |
| 17/7–2/8 | 2 | 29 | 31 | 0 | 31 | 134 |
| 2/8–13/8 | 19 | −4 | 15 | 0 | 15 | 160 |
| 13/8–3/9 | 76 | −36 | 40 | 24 | 16 | 191 |
| 3/9–12/9 | 19 | 14 | 33 | 6 | 27 | 208 |
| 12/9–7/11 | 80 | −22 | 59 | 28 | 31 | 253 |

* Measured drainage through 50 cm bare soil nearby

In 1963 there was only one access tube in bare soil: measurements started in early June and then, and several times later, there was heavy rain. On at least two occasions (3 September and 7 November), and possibly on 12 June, it seemed that there was some flooding of the gap outside the access tube at the time of monitoring, so distorting the water balance for the period in the sense of under-estimating the apparent evaporation.



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Where the amount might be significant vertical arrows on Fig. 1, top, show, approximately, the scale of the effect. The figure shows clearly the contrast between the 'dry' weather behaviour (1962) and the 'wet' weather behaviour (1963).

### Short turf, 1963–64, 1971

**1963–64.** During autumn 1963 one access tube was set in the meteorological enclosure under grass kept short by regular mowing, and readings were taken, 0 to 90 cm, at

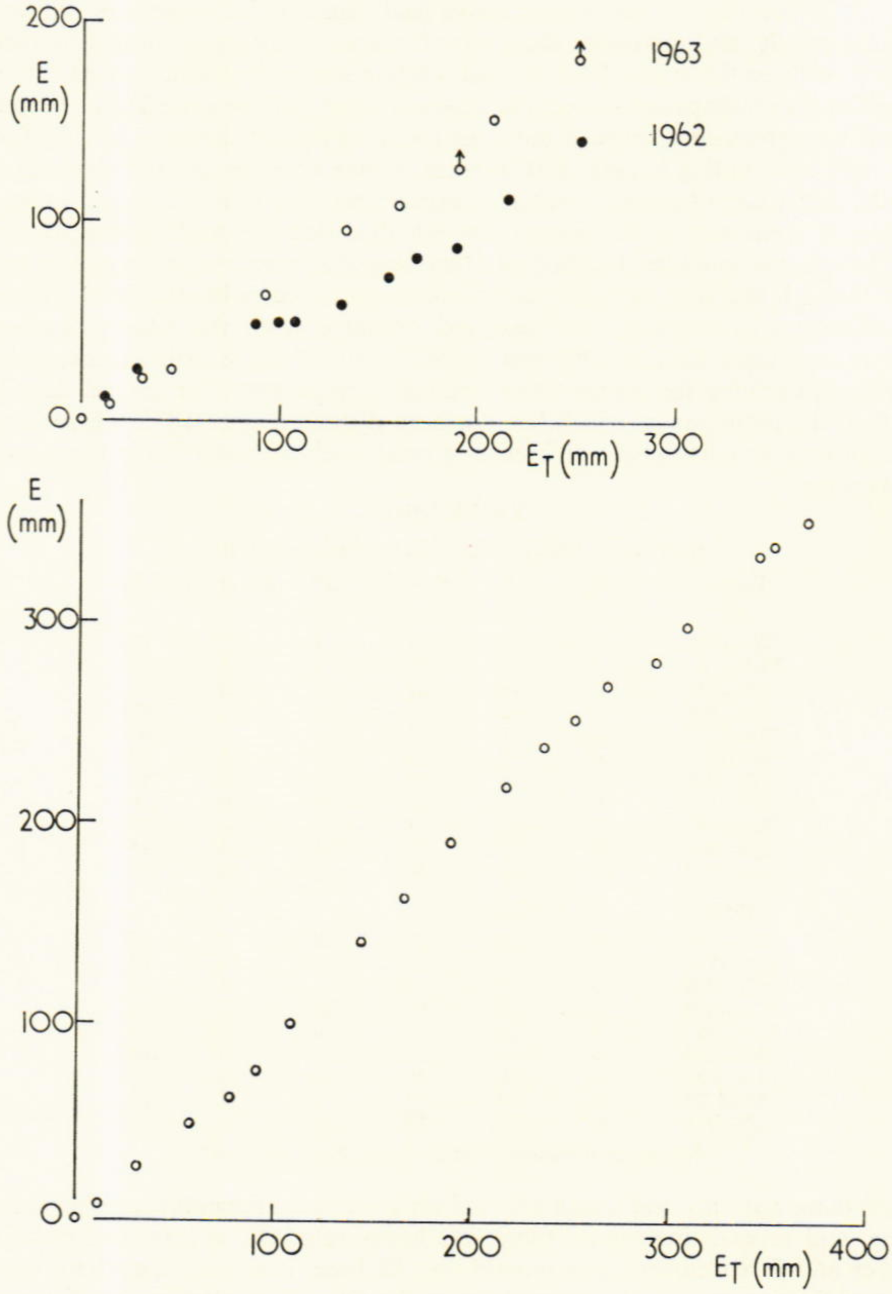


FIG. 1 (III). Top. Evaporation from bare soil, 1962 and 1963. Bottom. Evaporation from short turf, 1971.



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intervals until mid-June 1964. There were only two short periods free from certain or suspected drainage. For these—perhaps fortuitously—the hoped-for agreements between $R + D$ and $E_T$ were very good:

13/9 to 10/10, 1963. $R + D = 29$; $E_T = 28$ mm
14/5 to 16/6, 1964. $R + D = 86$; $E_T = 88$ mm

**1971.** A much more comprehensive set of measurements was obtained in 1971 when duplicate access tubes were set under the short turf and monitored 19 times between late April and early October, to a depth of 150 cm. The time changes, layer by layer, showed clearly that the space outside the W access tube was flooded more than once, 120 to 150 cm, and for this site the water balance is based on changes 0 to 120 cm. At the E site the whole profile, 0 to 150 cm, is used. With this adjustment the duplicates agree very well, and outstandingly so in the very wet period 7 to 23 June (98 mm of rain) when the measured gain of water was 58 mm at both sites ($\Sigma E_T$ from 108 to 145 mm): there may have been a few millimetres of drainage in this period, but there is no evidence to confirm the suspicion.

Fig. 1, bottom, shows the seasonal trend in measured evaporation, and the general slope is near unity. The late divergence (near $E_T = 270$ mm) corresponds to a time of maximum deficit, at *c.* 95 mm at the beginning of August, and this is probably a fair measure of the root constant of the mixture of grasses and weeds on the site, and in accord with expectation. Much more important—and unresolved—is the behaviour in the first five periods and the apparent recovery in the sixth. Close probing of the measurements and of the calculations of $E_T$ offers no clue. The whole season water balance of Table 2 shows the good agreement between duplicates at all depths, and the small amount of water abstracted from below 90 cm depth in the profile. The monitoring depth used, 1963–64, was probably adequate.

**TABLE 2(III)**

*Short turf. Water balance (mm)*

27 April to 6 October 1971

| | Site: | E | | W |
|---|---|---|---|---|
| $D$ | 0–60 | 80 | | 84 |
| | 0–90 | 100 | | 99 |
| | 0–120 | 106 | | 103 |
| | 0–150 | 108 | | 105 |
| $R$ | | | 245 | |
| $R + D$ | (0–120) | | | 348 |
| | (0–150) | 353 | | |
| $E_T$ | | | 369 | |

## Winter wheat, 1962

Later sections will deal with particular crops in groups of years, but it is convenient to consider the 1962 wheat and 1963 barley separately, because the work with the meter was still exploratory, the source of neutrons was still short-lived, and irrigation did not become part of the experiment until 1964. The measurements on wheat produced nothing of agronomic value, but, with all the later experience to guide, it did repeat two aspects of distorted readings already noted. The crop was drilled in autumn 1961, and at the first of duplicate monitorings on 24/25 May 1962 there was a good plant cover. There were frequent measurements (23 at one site, 18 at the other) but analysis was restricted to six sets at about three-week intervals up to early September. By this time there was a difference of 20 mm in the two estimates of water use with an average near 230 mm. The estimated potential evaporation for the period was 240 mm. It is clear from the profiles



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of water content with depth that there was extraction of water from below 90 cm (the limit of measurement), so that the true water use was certainly greater than 230 mm, and was probably greater than 240 mm. The first part of June provided some severe drying weather and there was, as in 1969 (Part II), evidence of apparently exaggerated drying, as indicated by the meter, with $\kappa = E/E_T \gg 1$. Yet, from the whole season balance, there was later recovery to $\kappa \geqslant 1$, behaviour compatible with soil shrinkage in the top layer during the rapid drying phase, and re-swelling later.

### Barley, 1963

Variety Proctor was drilled on 22 April, and by the end of May the crop was 17 cm tall, with about 40% cover. By the end of June cover was complete, crop height was 65 cm and later reached 105 cm (end of July). By 11 August leaves were dead; harvest was on 15 September. Several access tubes were installed during May, but only three (1, 2 and 4)

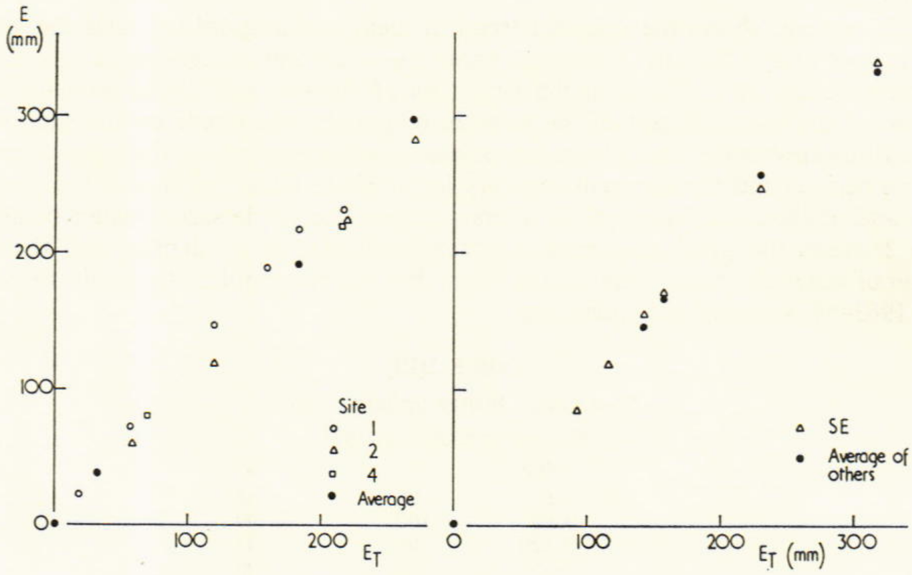


FIG. 2 (III). Evaporation from barley. Left, 1963. Right, 1965.

were monitored frequently enough to be useful, and not simultaneously. The depth of monitoring was only 90 cm, but because the summer was wet, the interpretative problems were more concerned with drainage than with possible drying deeper in the profile. For two periods of excessive rain, and presumed drainage, estimates of probable evaporation had to be made indirectly, as follows. A first trial showed that $\Sigma(R + D)$ was nearly equal to 1·1 times $\Sigma E_T$, and, to bridge gaps, it was assumed that the actual evaporation $E \equiv 1{\cdot}1\ E_T$ for the period. Were this all, it could be accepted as satisfactory, but there were other minor puzzles, not resolved, in cross-comparisons of meter behaviour at the three sites, leaving some uncertainty about the reliability of the results. Figure 2, left, shows the estimated evaporation from 31 May, the date of the first readings at site 1, with an allowance of 1·1 $E_T$ for sites 2 and 4 up to the dates (12 and 11 June) of their first measurements. The general slope is near 1·1, and, not revealed by the figure, the maximum deficit was about 70 mm (end of July: $\Sigma E_T = 160$ mm), and there is no obviously detectable check to transpiration at that time.



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## Grass, 1964

This was the first year of the Rothamsted irrigation experiment on Great Field, so giving the opportunity to measure water use with some degree of control over availability on the soil. As it happened, there was no need of irrigation until the end of June, and then it could not be met until some engineering defects in the installation were cured. Although other crops were irrigated, the neutron meter measurements were restricted to an area of grass, drilled 1 May 1964 on two main blocks of four main plots each in an area roughly $60 \times 120$ m. Each of the eight plots was split into four subplot strips that received different amounts of nitrogen fertiliser, first as a basal dressing in the seed bed, and then again after the cutting on 22 July. All the access tubes were in plots for which the unit application was 75 kg $ha^{-1}$ N as 'Nitro-Chalk'. The subplots were, in fact, too small, and in later years macroplots, $100 \times 100$ m, were used with uniform treatment over the whole area.

Two kinds of grass were used, Meadow Fescue, known to send down a fairly deep root system, and Timothy, which is relatively more shallow rooting. Access tubes were installed in all of the main plots, giving duplicate measurements for each of the four main experimental comparisons of Fescue (F) *v.* Timothy (T) and Irrigated (I) *v.* Unirrigated (O). Readings were taken, usually on all eight sites, at about weekly intervals from mid-June to early October, with a few sites monitored late in November. The grass grew fairly well from emergence (near 13 May) to heights of 35 cm (F) and 25 cm (T) when cut back to 5 cm on 22 July. The irrigation was applied in the period before the second cut on 6 September, and at this time the heights were: FI, 35; FO, 20; TI, 20; TO, 10 cm. Growth continued until mid-October, when the heights were: FI, 20; FO 15; TI, 12; TO, 7 cm. Expectation is that the crop will be intermediate in roughness between short turf and a cereal.

Immediately after the first measurements on 15 June there was heavy rain that probably produced some drainage and, much more important, almost certainly left the air gaps outside the access tubes waterlogged at the next set of measurements on 22 June. So the

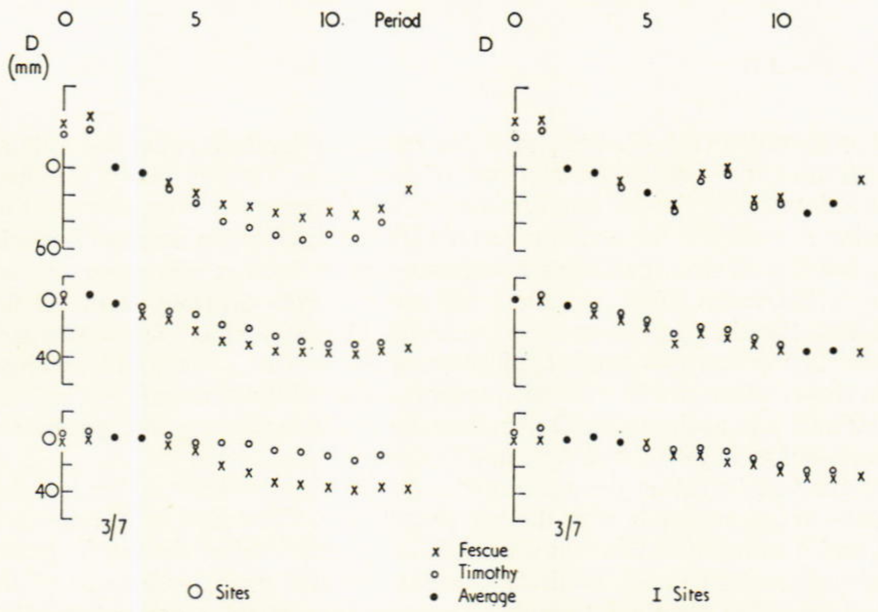


FIG. 3 (III) .Drying by layers, Meadow Fescue and Timothy, 1964. Working zero, 3 July. Left, O sites; right, I sites. Averages are given where points are not separable.



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apparent drying between 22 June and 3 July is a grievous over-estimate, and in processing the records 3 July has been used as effective zero time, but Fig. 3 shows the measurements made in the two preceding periods.

The neutron source was still the Polonium 210/Berylium with the short half-life, the operational skill in handling the equipment was not yet as marked as it later became, and circuitry still needed improvement, so there were occasions on which expected agreements between duplicate measurements were not obtained. With no convincing reasons for rejecting anything, all measurements after 3 July were retained, with duplicates and grass varieties averaged for Fig. 4. The main source of uncertainty in the end is ignorance of what happened below 90 cm depth: the monitoring did not go deeply enough.

**Drying by layers (Fig. 3).** Starting from a zero at the end of Period 2, Fig. 3 shows the contrast between the two grasses. Clearly the unirrigated Timothy (circles) has taken more water out of the top 30 cm of soil than the Fescue, a little less from 30 to 60 cm, and much less from 60 to 90 cm. The totals, 0 to 90 cm, do not differ very much (see Table 3). For the irrigated crops there is no real difference in any layer—and a hint of a puzzle. The irrigated Timothy seemed to take more water from the 60 to 90 cm layer than the unirrigated, whereas the Fescue took less, as might have been guessed.

**TABLE 3(III)**

*Grass, 1964. Curtailed water balance (mm)*

| Period | $R$ | Nominal $I$ | Average drying $\bar{D}$ FO | TO | FI | TI | $R + \bar{D}_O$ | | $R + I + \bar{D}_I$ | $\Sigma E_T$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 15/6–3/7 | 37 | | ? | | ? | | | 46? | | 46 |
| 3/7–28/7 | 31 | | 37 | 44 | 37 | 35 | 71 | | 67 | 120 |
| 28/7–13/8 | 3 | 51 | 29 | 34 | −6 | −2 | 35 | | 50 | 165 |
| 13/8–27/8 | 9 | 25 | 17 | 16 | −6 | −3 | 26 | | 30 | 193 |
| 27/8–28/9 | 19 | | 16 | 10 | 55 | 58 | 32 | | 75 | 253 |
| 28/9–9/10 | 12 | | −14 | −13 | −7 | −8 | −1 | | 4 | 264 |
| 9/10–25/11 | 35 | | | −24 | | | | 11 | | 275 |
| 3/7–28/9 | 62 | 76 | 102 | | 84 | | 164 | | 222 | 207 |
| Possible extra in deeper profile | | | 35 | | 10 | | | | | |
| Corrected: 15/6–25/11 | | | | | | | 255 | | 293 | 275 |

**Possible evaporation (Fig. 4).** Because of the restricted depth, evaporation estimates are almost certainly too small in the later part of the season. The real zero of the diagram is the first full point (for 3 July) but, for interest, the diagram has been plotted as from 15 June, using $E = E_T$ for the first two periods (18 days). Only the nominal irrigation was known, but the internal consistency suggests that in total it was close to what was received at the access tubes, but there was some uneven distribution in the first two applications. For the figure these two (nominally 13 and 38 mm, a few days apart) have been brought together as a single application of 51 mm (see Table 3). In two places the diagram shows where results have been accepted with a little disbelief: on the I line near $E_T = 190$ mm and again on the O line, near $E_T = 260$ mm, the (short) period evaporation comes out as negative, and no cause is known.

Up to the first irrigation the agreement is good—all plots have so far had the same treatment—but immediately after the two sets diverge. The deficit at this time was near 60 mm, and it is almost certain that water had been needed before the first irrigation (held back by engineering trouble, as already noted), and it is probably because of this that there is a small but clearly detectable change in slope of the I points from this stage onward, from near unity to about 1·1 or 1·2.



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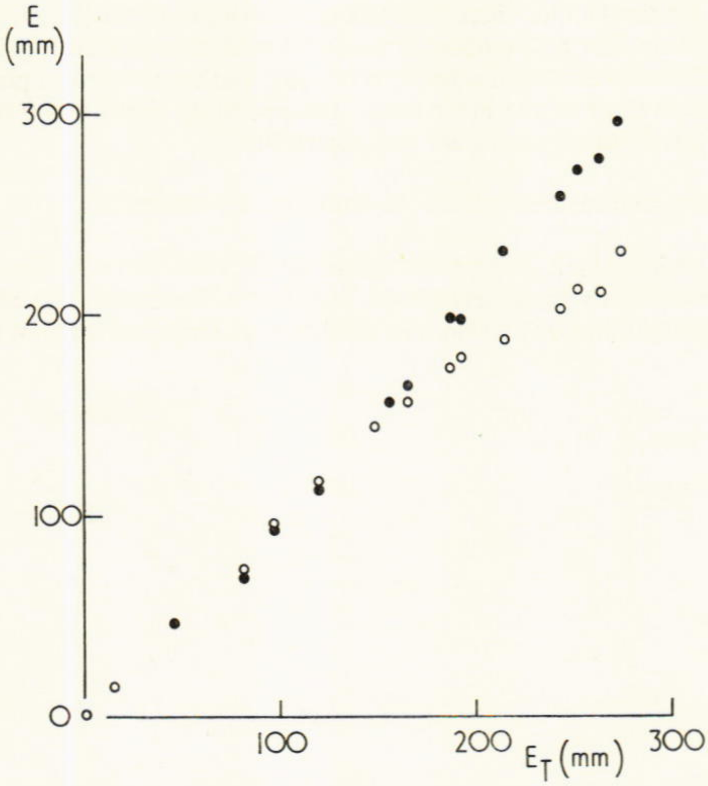


FIG. 4 (III). Evaporation from grasses (average of two). Full points, I sites; open points, O sites.

**More probable evaporation (Table 3).** Down to 90 cm the results for grass (Fig. 3) show much the same pattern as those for barley in 1970 (Part I, Fig. 4), and to get at least the scale of deeper drying it is assumed that the pattern was the same for both below 90 cm depth, imposing the condition that the drying, 90 to 150 cm, was the same fraction of that 0 to 90 cm for both crops, treating O and I results separately. The effect is in the last line of Table 3, where it is applied to the measurements on 28 September, the epoch of maximum drying in the profile.

## Crops in rotation

### 1. Barley 1965, 1967

As set out in Part I the site has three main areas, two (Xn and Xs) used for conventional irrigation experiments, and the third, with only two large areas, each 100 × 100 m, is uniformly treated to avoid the undesirable patchiness produced by randomisation and replication of differing treatments. These are, in effect, outdoor physics laboratories, with the boundary conditions chosen for meteorological reasons, and the test crop chosen mainly for some desired attribute in growth habit or morphology.

In general the crops on the macroplots, Mn and Ms, have had four access tubes in each of the irrigated (I sites) and unirrigated (O sites) areas, while the experimental areas (Xs and Xn, each with a different crop) had duplicate measurements at I and O sites.

**1965.** Little of value came from the 1965 measurements. The summer was wet, and the only brief interlude when irrigation of the barley was called for was succeeded by more rain. Few measurements were made, and those on the I sites were too chaotic to be worth



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reproduction. At the O sites there were six monitorings at one (SE) from 14 June to 4 October and only four at the other three. In processing to obtain Fig. 2, right, it was assumed that the soil was at field capacity on 7 May, and the two sets of points are for the SE site and the average of the other three. The operating depth was 0 to 150 cm. The consistency is good but all results are very uncertain.

**1966.** There were no measurements on the barley grown on area Xs.

**1967.** In 1967 variety Maris Badger was drilled on 13 March on area Xn and there were 16 sets of measurements made between 11 May and 6 September, two after harvest on 22 August. The depth was 0 to 90 cm. For the first time, irrigation amount was monitored

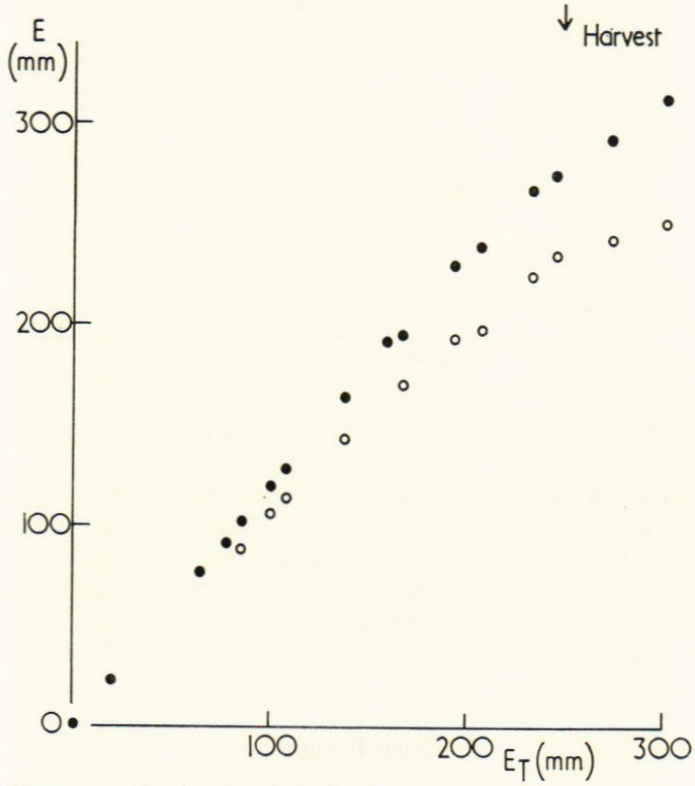


FIG. 5 (III). Evaporation from barley, 1967. Full points, I sites: open points, O sites.

by the five collectors around each access tube, agreements between duplicate averages were fairly good, and against a nominal total of 102 mm in four equal applications the measured totals were 121 mm at site SE, and 109 mm at site SW. In the second period, 22 May to 9 June, there was a lot of rain, producing drainage that cannot be estimated: for this period the evaporation is assumed to be 1·2 times $E_T$ for the period (all plots were effectively O plots at this stage). Similarly, in Period 7 heavy rain came after irrigation and the same assumption was made to estimate $E_I$ for the period. On two occasions monitoring followed much too quickly on an irrigation operation and, on the first, at site SW, and on the second, at site SE, there was circumstantial evidence of flooding at the access tubes. For the pairs of periods so affected (4 and 5; 9 and 10) the doubtful measurements were ignored.

The crop emerged at the beginning of April, was about 15 cm tall on 11 May, about



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60 cm at the time of the first irrigation (12 June), and reached 100 cm by mid-July. At these three stages the fraction of cover was 30, 55 and 60% (the maximum). The crop was ripe by 3 August and cut on 22 August.

The evaporation estimates on Fig. 5 are probably too small because of the restricted depth of monitoring. After the zero, the first two points are averages of four: thence they are averages of two (except as already noted). For the I sites (full points) the general slope during the main growing season is near 1·2—so justifying the choice of weighting factor used to bridge two gaps. The summary water balance sheet (Table 4) gives totals up to harvest and shows the inferred amounts of drainage for these two particular periods. The agreement in the two values of $R + I + D$ for the I sites is a freak result.

**TABLE 4(III)**

*Barley, 1967. Water balance to harvest (mm)*

| | | O Average of 2 | $I$ SE | $I$ SW |
|---|---|---|---|---|
| Total rain, $R$ 11/5–8/8 | | 191 | 191 | |
| Total $I$ | | — | 121 | 109 |
| Measured $D$ | | 65 | 14 | 26 |
| $R + I + D$ | | 256 | 326 | 326 |
| Processed $E$ | | 235 | 277 | |
| Presumed drainage | | | | |
| 22/5–9/6 | $R = 51$ | 20 | 20 | |
| 22/6–3/7 | $R = 51$, $I = 32$ | 0 | 29 | |
| $E_T$ | | 245 | | |

## 2. Beans 1965, 1966, 1967, 1971

**1965.** In the wet summer of 1965 the beans grown on site Xn, monitored to 90 cm, were irrigated once and meter readings were taken only on 3 June, before irrigation, 4 June, and on 7 September. There may have been some drainage during three wet weeks in July. The duplicate measurements agreed quite well and the extra evaporation from the irrigated plots is probably real. From 3 June to 7 September the average water balances were:

O sites $R = 217$, $E_O = 192$ mm
I sites $R = 217$, $I = 14$, $E_I = 204$ mm, $E_T = 221$ mm

**1966.** In 1966 the beans were on the macroplots with four access tubes in each (O, Ms; I, Mn) to 150 cm. The crop (Maris Bead) was drilled on 10 March, and at the time of the first monitoring it was 30 cm tall. Most later growth was good. By mid-July plants at O sites were about 130 cm tall, and at three I sites they were 150 cm tall. At one I site (NE) growth was poor (height, mid-July 120 cm), and in the processing towards Fig. 6 results from this site are ignored, but they appear in Table 5. The leaf area index (I sites) was about unity at the first monitoring (1 June), was 3 by mid-June ($E_T \simeq 50$ mm), 7 by the end of June ($E_T \simeq 90$ mm), reached a maximum of 8·5 on 25 July ($E_T \simeq 160$ mm), and thereafter rapidly decreased through 4 on 8 August ($E_T \simeq 180$ mm), and 3 on 24 August ($E_T \simeq 220$ mm); at harvest on 24 September there were few green leaves anywhere.

There were several wet periods in the summer, one immediately after the second irrigation—rendering it superfluous and producing drainage. To get an estimate of amount Fig. 6, inset, was prepared to show the measured changes in soil water content between 1 June, and 13 July when the soil was at its driest. The accumulated net drying, by 30 cm layers, is plotted downward as $D_O$ or $D_I$, and the difference, $\bar{D}_O - D_I$, is plotted upward. It is a fair assumption, supported by evidence in Fig. 6, that up to this time there was no



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significant difference in the total evaporation from the two sets of sites, and hence the gap between the limiting value of $D_O - D_I$ and the applied irrigation, $\Sigma I$, is a measure of the extra drainage through the irrigated plots. The value is 23 mm. This correction is applied to I site measurements for the period 9 to 16 June (rain = 30 mm), the third on Fig. 6 for the I sites in 1966. This shows a discontinuity in the trend of $E$ against $E_T$, possibly because of temporary flooding of the gaps round access tubes in the fourth I period (rain, 49 mm).

The general slope is near unity, and Fig. 6, inset, shows that the unirrigated crop took most of its water out of the top 90 cm of soil while the irrigated crop tapped little more than the top 60 cm. The evidence of nearly equal and uniform drying below 90 cm may indicate some downward drainage from both sets of profiles.

**TABLE 5(III)**

*Beans, 1966, Seasonal water balance (mm)*

| | | I sites | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | NE | SE | SW | NW | $R$ | Assumed or inferred $d$ | $E_T$ |
| 31/5–12/7 | $D$ | 47 | 31 | 24 | 41 | 94 | 23 | 122 |
| | $I$ (Nom.) | 35 | 35 | 35 | 35 | | | |
| 12/7–12/9 | $D$ | −50 | −26 | −15 | −46 | 138 | 0 | 136 |
| | $I$ (Nom.) | 25 | 25 | 25 | 25 | | | |
| Total | | 57 | 65 | 69 | 55 | 232 | 23 | |
| $R + I + D - d$ | | 266 | 274 | 278 | 264 | | | 258 |
| | | O sites | | | | | | |
| 1/6–13/7 | $D$ | 42 | 34 | 44 | 58 | 94 | | 128 |
| 13/7–13/9 | $D$ | −19 | −24 | −27 | −30 | 138 | | 134 |
| Total | | 23 | 10 | 17 | 21 | 232 | | |
| $R + D$ | | 255 | 242 | 249 | 260 | | | 255 |

Table 5 gives a two-part summary of the water balance for each treatment, first for the drying period to 12 July, and then for the re-wetting to 12 September. Over both the NE I results are in no way discordant, and it would seem that the poorer growth there had no important dependence on the amount of water used in producing it.

**1967.** The summer of 1967 was much drier, except for wet periods at the end of May and at the end of June, and irrigation of beans was thought worthwhile on five occasions when equal nominal amounts were given, totalling 127 mm. The measured amounts, as averages for five rain collectors at each site, were in good agreement with each other on all occasions, and with the nominal amounts. The totals were: NE, 119; SE, 118 mm. There was a double contrast with 1966: many more monitorings were done, but only to 90 cm.

The crop (Maris Bead) was drilled on area Xs on 20 March, and at the time of the first monitoring (16 May) was 10 cm tall. In the next three weeks there was excessive rain, with drainage, and in effect the zero date (as for Fig. 6) is 9 June, when the crop was 45 cm tall and giving 35% cover. Crop height increased to 150 cm by early August, with 100% cover that then fell away to about 50% by early September.

On most of the occasions, an attempt was made to monitor the access tubes on the morning before an afternoon irrigation and then again next morning. This was a waste of time. The flooding of the gaps outside the access tubes distorts the apparent gain of water, and the result is a seemingly negative evaporation on the day of irrigation. Normal processing would simply disregard these distorted second day readings, but they have



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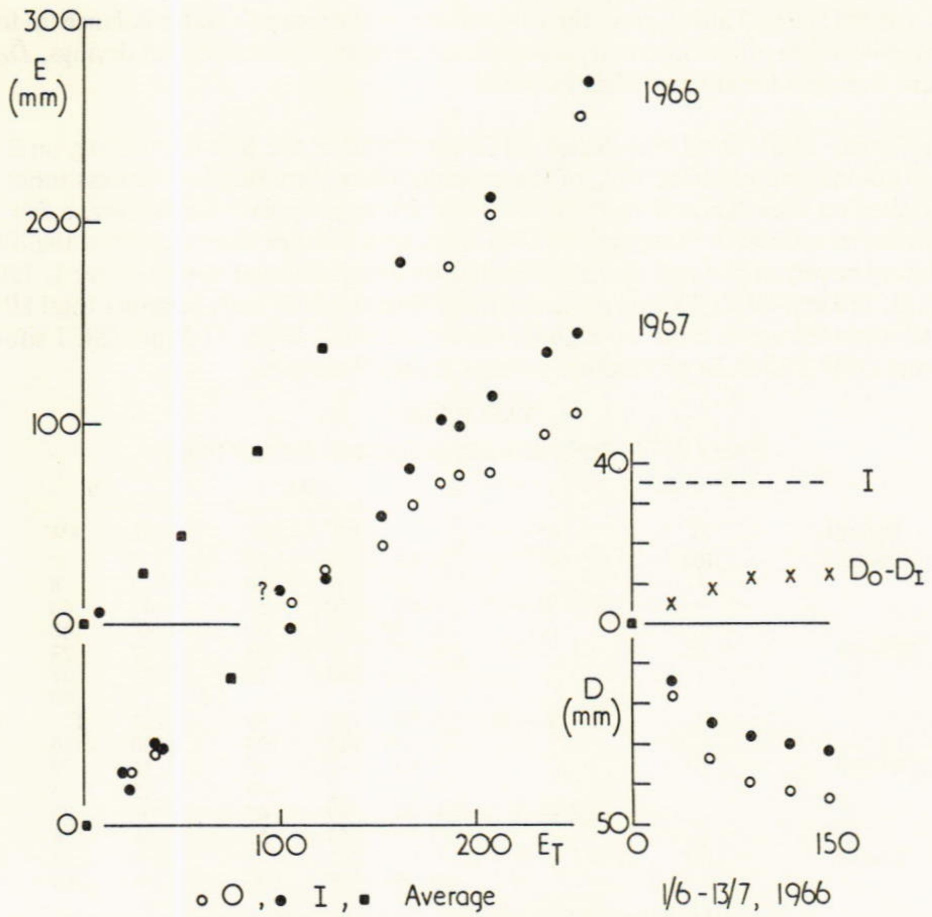


FIG. 6 (III). Evaporation from beans, 1966 and 1967. Averages are given where points are not separable. Bottom right: Average drying, 1 June to 13 July, 1966, and $D_O - D_I$ compared with applied irrigation I.

been left in here because part of the objective is to show what the neutron meter can do, and it may be informative to show how it should not be used. There are clear examples for the first, second and fifth irrigations, with that for the third irrigation exaggerated by a fault in meter performance before the irrigation (queried at the time, on site, and given a question mark on Fig. 6). There was no evidence to suggest any drainage at O sites, but there almost certainly was some drainage at I sites in the period after the second irrigation, when $R = 51$ mm. In the light of the trend in Fig. 6, the evaporation was set as $E = E_T = 74 - 39$ mm, implying a drainage loss of about 37 mm in this period. Because of the spacing of the irrigations there is probably no major loss of information about $E_I$ arising from the limited depth of monitoring, but the unirrigated plants probably took water from below 90 cm, and the difference of 40 mm in total water use on Fig. 6 is almost certainly too big. At the divergence of $E_I$ and $E_O$, $D_O$ was near 70 mm.

**TABLE 6(III)**

*Beans, 1967. Water balance (mm)*

| Period | $R$ | $\bar{D}_O$ | $R + \bar{D}_O$ | $I$ | $\bar{D}_I$ | Est. $d$ | $R + I + \bar{D}_I - d$ | $E_T$ |
|---|---|---|---|---|---|---|---|---|
| 9/6–10/8 | 112 | 58 | 170 | 93 | 35 | 37 | 203 | 182 |
| 10/8–22/9 | 71 | −36 | 35 | 26 | −54 | 0 | 43 | 69 |
| Total | | | 205 | | | | 246 | 251 |



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As a supplement, Table 6 gives the components in the season's water balance up to and after the occasion of maximum dryness on the unirrigated plots. The net dryings, $\bar{D}_O$ and $\bar{D}_I$, are averages for the two sites for each.

**1971.** Variety Maris Bead was drilled on 30 April and at the first monitoring on 2 June was 10 cm tall and covering 20% of the ground. There were duplicate access tubes at O and I sites on area Xn and there were 13 monitorings up to 9 September, a few days before harvest. Growth was good on both sites, with I better than O, and at the time of maximum cover, at the end of July, the heights and fractional covers were: I, 120 cm, 90%; O, 110 cm, 80%. The crop was irrigated four times in July, nominal total 80 mm, and all expected agreements were good, the actual totals being 77·5 mm (SE I site) and 76·5 mm (NW I site). In processing, average values were used.

**TABLE 7(III)**

*Beans 1971. Periodic water balance to harvest (mm)*

| | | | | | $D_O$ | | | $D_I$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Periods | | $R$ | $d$* | | NE | SW | | SE | NW | $E_T$ |
| 1–3 | 2/6–29/6 | 104 | 64 | 0–60 | 10 | 11 | | 9 | 8 | |
| | | | | 0–150 | 13 | 10 | | 8 | 8 | |
| | | | $R + D - d$ | 0–60 | 50 | 51 | | 49 | 48 | 65 |
| | | | | 0–150 | 53 | 50 | | 48 | 48 | |
| 4–8 | 29/6–4/8 | 28 | | 0–60 | 76 | 55 | | 17 | 23 | |
| | | | | 0–150 | 85 | 76 | | 25 | 31 | |
| | | | | | | | $I$ | 77 | 76 | |
| | | | $R + I + D$ | 0–60 | 104 | 83 | | 122 | 127 | 107 |
| | | | | 0–150 | 113 | 104 | | 130 | 136 | |
| 9–12 | 4/8–9/9 | 51 | | 0–60 | −2 | −6 | | 11 | 19 | |
| | | | | 0–150 | 2 | −0 | | 15 | 25 | |
| | | | $R + D$ | 0–60 | 49 | 45 | | 62 | 70 | 67 |
| | | | | 0–150 | 53 | 51 | | 66 | 76 | |
| 1–12 | 2/6–9–9 | 183 | $R + I + D - d$ | 0–60 | 203 | 179 | | 233 | 245 | 239 |
| | | | | 0–150 | 219 | 205 | | 244 | 260 | |

* Measured drainage through 50 cm bare soil nearby

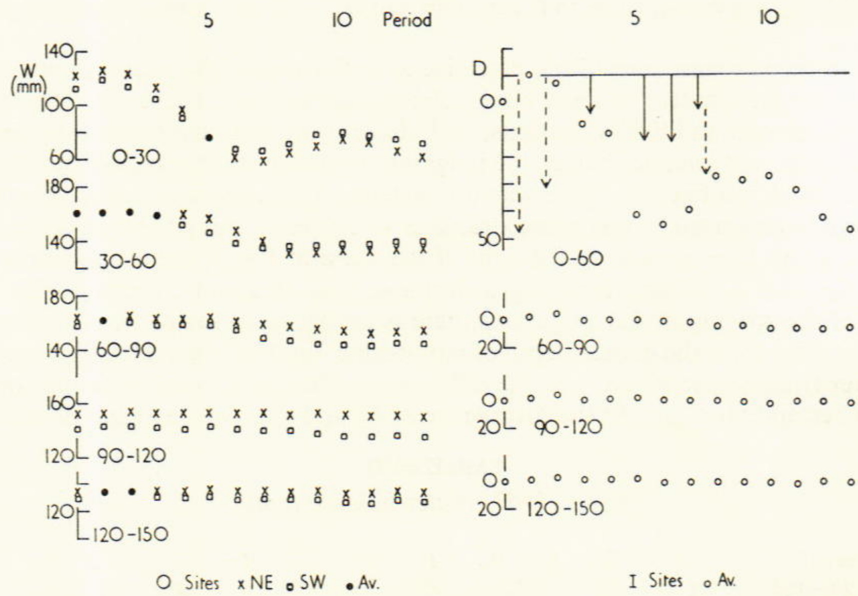


FIG. 7 (III). Drying by layers, beans 1971. Left, absolute water content at O sites. Right, I sites with 0 to 60 cm on more open scale, and irrigation and major rain added.



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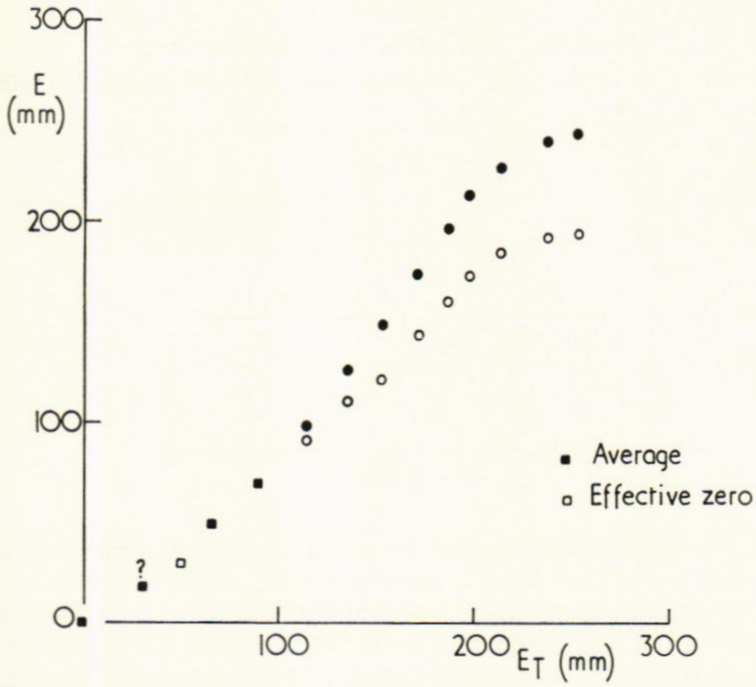


FIG. 8 (III). Evaporation from beans, 1971. Effective zero at end of Period 2. Full points, I sites: open points, O sites.

The first two periods (up to 24 June) were very wet, with certainty of drainage, so to get at least the scale of possible water use it was assumed that the drainage was equal to that through the 50 cm deep bare soil drain-gauge nearby (Table 7), and the effective zero date for forward computation was from the end of Period 2 (Fig. 8). Study of the layer-by-layer drying (Fig. 7) for both O and I sites, suggested, fairly strongly, that below about 60 cm depth a small amount of apparent drying was probably slow drainage of water that had accumulated in the wet period of early June: for Fig. 8 the values of $D$, 0 to 60 cm, are used, and Table 7 shows, for grouped periods, what was omitted by this decision. This, of course, is a departure from previous general policy in processing the records, but the change could be justified by a rather long argument.

The general slopes of points on Fig. 8 are near 1·2 (I sites) and 1·0 (O sites), and the two sets of points diverge at about $E_T = 90$ mm when a very rough estimate of soil moisture deficit was 30 mm. This is surprisingly small, but may be an indication that the wet soil during the first three weeks of June limited root growth and subsequent activity was restricted to the top 40 or so centimetres of soil—an inference in accord with the decision to restrict the water balance to the top 60 cm.

### 3. Potatoes 1965, 1966, 1971

**1965.** As for the barley and the beans the summer was too wet to produce anything very useful. Grown on area Xs, the Majestic potatoes had duplicate access tubes to 90 cm at O and I sites. The entries in Table 8 are averages of two, weighted by the factor 2/3 for the top 20 cm (see Part II). The only irrigation, nominally 25 mm, was applied just before the wet period 8 July to 12 August, and the immediate monitoring after irrigation produced a distortion in the opposite sense to that noted for the beans in the preceding section (see Fig. 8). The access tubes were in the ridges, and the shedding of water by the



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TABLE 8(III)

*Potatoes, 1965, 1966. Water balance (mm)*

| Period | $R$ | $\bar{D}_O$ | $\bar{D}_I$ | $I$ (Nom.) | $E_T$ | Derived quantities or inference |
|---|---|---|---|---|---|---|
| 1965 | | | | | | |
| 11/6–5/7 | 43 | 25 | 20 | | 69 | $E_O = 68$; $E_I = 63$ ($\simeq E_T$) |
| 5/7–7/7 | 0 | | −13 | 25 | 5 | $\mid D_I \mid$ too small |
| 5/7–8/7 | 0 | 3 | | | 7 | |
| 7/7–12/8 | 126 | | −3 | | 77 | Possible drainage: $d_I = 46$ |
| 8/7–12/8 | 126 | −17 | | | 75 | Possible drainage: $d_O = 34$ |
| 12/8–6/9 | 36 | −9 | −9 | | 46 | $E_O = E_I = 27$ ($< E_T$) |

| Period | $R$ | $D_O$ | | | $D_I$ | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1966 | | M | KE | $R + \bar{D}_O$ | M | KE | $\bar{I}$ | $R + \bar{I} + \bar{D}_I$ | $E_T$ |
| 22/6–25/7 | 79 | 26 | 21 | 103 | −2 | −7 | 28* | 103 | 87 |
| 25/7–9/9 | 110 | −13 | −5 | 101 | −1 | −12 | 0 | 104 | 98 |
| Totals | 189 | 13 | 17 | 204 | −3 | −18 | 28 | 208 | 185 |

* From 26 − (− 2) M
21 − (− 7) KE

Nominal $I = 25$

plant steered too much toward the furrow bottom, outside the range of action of the meter. In the first period the water use was about equal to the potential evaporation rate. Between 7 July and 12 August there was drainage, estimated in Table 8 by assuming $E = E_T$ for the period, and thence to 6 September the water use was the same for both irrigated and unirrigated plots, and less than the potential evaporation rate, $E_T$.

**1966.** Though here too only one irrigation was called for (nominally 25 mm) the later weather was no worse than wet enough to remove the need for more irrigation without any strong suspicion of drainage: the results are a little more informative than those for 1965. Two varieties (Majestic, M; and King Edward, KE) were grown on area Xn at 38 cm spacing in rows 71 cm apart. One access tube, to 90 cm, was set in a plot of each, at O and I sites, but, though there was no duplication, the two varieties showed no difference in behaviour greater than is obtained from duplicate treatments of the same variety of other crops, and in most of the analysis the average was used. The difficulties of interpreting results for potatoes have already been stressed (Part II) and the minor irregularities in the figures and the table show evidence of them. In addition, there were two occasions on which measurements are suspect, one immediately after the irrigation at the M I site, the other after the wet period 25 July to 5 August, at the KE O site, both showing what seem to be excessive gains of water. Both were retained and used.

As before, the drying in the first 20 cm of soil is weighted by a factor 2/3, and it is the weighted values that appear on Fig. 9, left, where the periods are for O sites. The irrigation, on 13 July, was preceded by measurements, on I sites only, on 12 July: all sites were monitored on 14 July (end of Period 3). Fig. 9 shows the drying by layers, from a zero on 22 June when the plants were 55 cm tall and ground cover was 60%. The two sets of points for each section are displaced for clarity and the important result is obvious: the separation is very constant at all levels before and after irrigation, with the step caused by the irrigation just detectable in the lowest layer. From general experience, the I value, 60 to 90 cm, is probably in error because of perched water round one access tube at the end of Period 5. The effect of the parallel trends is that the evaporation rate is the same for both O and I treatments and, with one exception, the points on Fig. 9, right, are averages of O and I results, already averaged for variety. The exception is the I site readings on 12 July, taken before the irrigation. This, nominally, was 25 mm, but for Fig. 9 the value $I = 28$ mm was used, a value that can be inferred in several ways from the detailed measurements and is here supported in one of them, in Table 8, which gives



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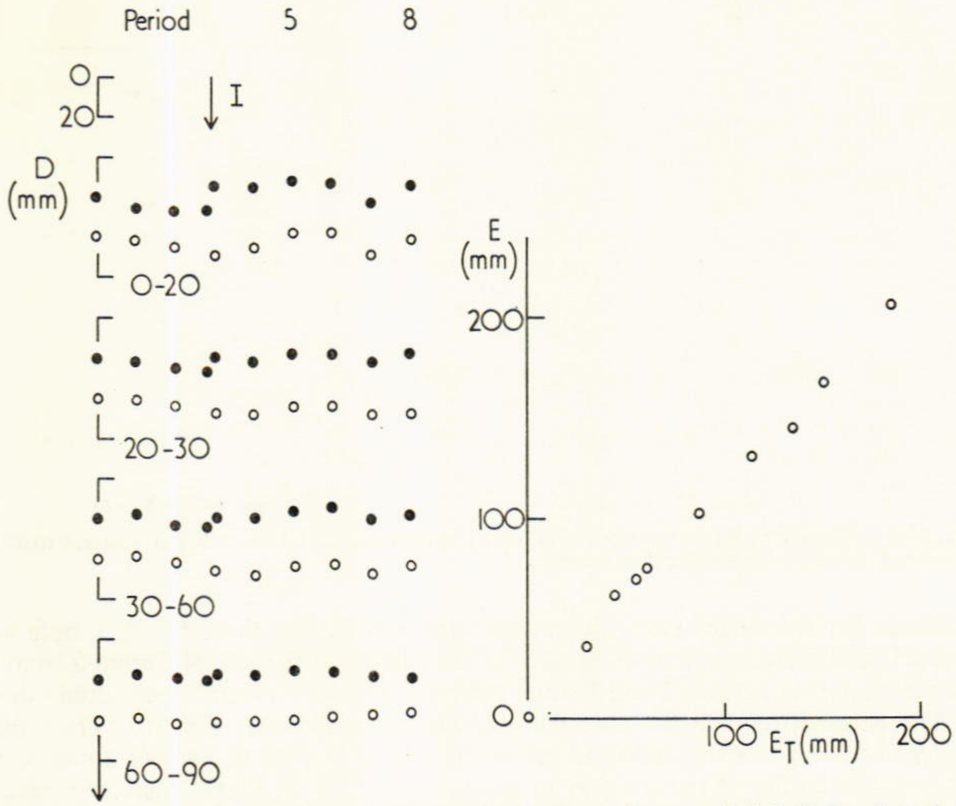


FIG. 9 (III). Left. Drying by layers, potatoes 1966 (average of two varieties). Full points, I sites; open points, O sites. There was an extra I reading in Period 3, before the irrigation. Right. Evaporation from potatoes 1966. (Average of O and I, and of variety).

a two-part seasonal water balance for the main drying period and the later re-wetting period. Here the varieties are separated, and the estimate of true irrigation is obtained from the values of $D_O - D_I$ assuming that the evaporation was the same at O and I sites (evidence on Fig. 9), and that there was no drainage from either. The exact agreement for the two varieties is fortuitous in the light of the other differences in the table, but even these are surprisingly small. The difference in total evaporation ($E_I - E_O$) is small, and it was not greater than this throughout the summer: hence the use of a general average in Fig. 9. Similarly the difference between varieties is within expected scatter. The general slope of points on Fig. 9 is near 1·05.

**1971.** Potatoes (King Edward) were on area Xs with duplicate access tubes on O sites (holes 1 and 3) and on I sites (holes 2 and 4). At the first monitoring (21 May) the plants were 10 cm tall and cover was 7%. The crop grew steadily to reach a maximum height near 75 cm which was maintained throughout July, and then steadily declined towards the burning off (15 September) before harvest. The cover was more variable, the general July value being near 80 or 90%, with an important exception: on 17 July it was only 50% at all sites because plants on all plots were wilting, though the I sites had received 25 mm of irrigation the day before. Presumably the regain of turgidity needed more than one day. (It was back to normal a week later.) The irrigation was the same as for the beans (four times: nominal total 80 mm), and duplicate measurements of actual water received at holes 2 and 4 agreed well with each other and with the nominal amounts, to give totals of 83·6 (hole 2) and 86·4 (hole 4) mm.



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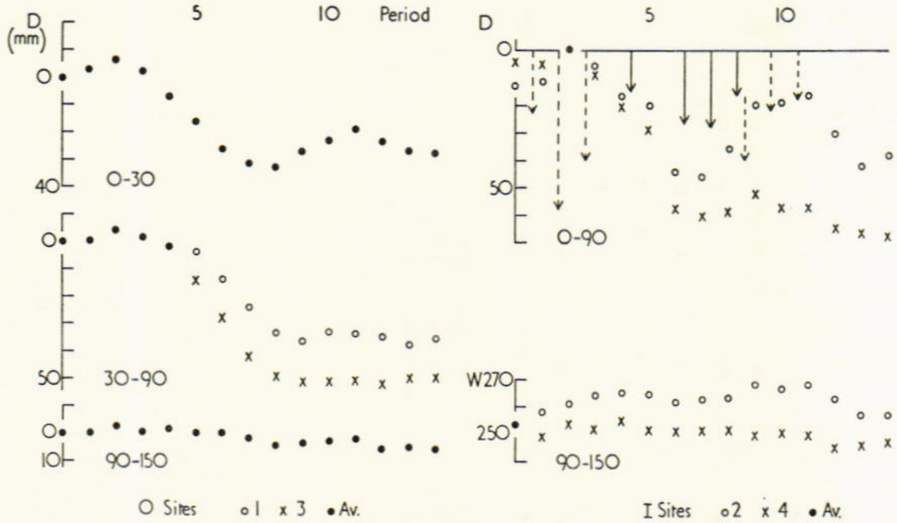


FIG. 10 (III). Drying by layers, potatoes 1971, on the open scale. Left, O sites. Right, I sites, 0 to 90 cm, with average irrigation and major rain added.

As usual for the ridged crop, the results were erratic, and those for each hole were processed separately, and a working zero of time taken at the end of Period 3 to avoid the uncertainties in Periods 2 and 3 when there was excessive rainfall, and certain drainage. The general trend in the next few periods was sufficiently clear to permit fairly confident backward extrapolation to get a probable $E$ in each of Periods 2 and 3, and hence a possible value of the drainage in these periods (2 to 24 June). Then the measured $R + D$ for the first period could be fitted on, to give the picture shown by Fig. 11. The estimate of possible drainage is near 45 mm, somewhat less than the amount estimated, in a different way, to have drained out of the bean plots (see Table 7).

Study of the periodic drying by layers shows (Fig. 10) that there was very little change in soil water content below 90 cm (from the *top* of the ridge), with the implication that the ridge itself steers both rain and irrigation water to the furrow bottom, too far from the access tube to be detectable, and the umbrella-like action of the plant does the same. The effect is to exaggerate estimated drying of the soil in wet periods, and hence the

**TABLE 9(III)**

*Potatoes, 1971. Periodic water balance (mm)*

| Period | | O sites: Hole 1 | O sites | O sites: Hole 3 | I sites: Hole 2 | I sites | I sites: Hole 4 | $E_T$ |
|---|---|---|---|---|---|---|---|---|
| 21/5–24/6 | $R$ | | 121 | | | 121 | | |
| | $D$ | | −4 | | | −6 | | |
| | Possible $d$ | | 47 | | | 42 | | |
| | $R + D - d$ | | 70 | | | 73 | | 79 |
| 24/6–13/7 | $R$ | | 6 | | | 6 | | |
| | $D$ | 46 | | 56 | 41 | | 50 | |
| | $I$ | | | | 16 | | 14 | |
| | $R + I + D$ | 52 | | 62 | 63 | | 70 | 64 |
| 13/7–4/8 | $R$ | | 27 | | | 27 | | |
| | $D$ | 22 | | 32 | −31 | | −4 | |
| | $I$ | | | | 68 | | 73 | |
| | $R + I + D$ | 49 | | 58 | 64 | | 95 | 57 |
| 4/8–27/8 | $R$ | | 48 | | | 48 | | |
| | $D$ | −3 | | −1 | 16 | | 17 | |
| | $R + D$ | 45 | | 47 | 64 | | 65 | 43 |
| | $\Sigma(R + I + D - d)$ | 216 | | 237 | 264 | | 303 | 243 |



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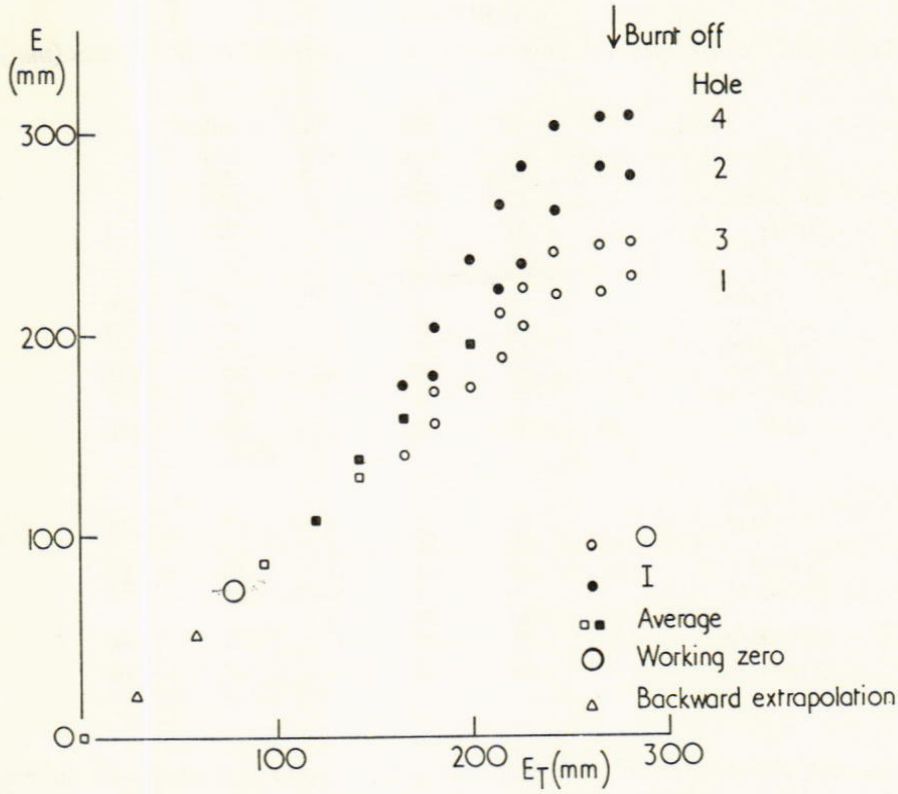


FIG. 11 (III). Evaporation from potatoes, 1971.

estimates of $E$ at I sites, for most periods, are probably too big. The unsatisfactory aspects of a ridged crop as the medium for neutron meter measurements make extended discussion rather pointless. Fig. 11 and Table 9 summarise the results in two ways and the only safe general conclusion is that the irrigated crop probably used more water than the unirrigated crop by an amount on the same scale as the differences between duplicate treatments. The separation, at about $E_T = 120$ mm, corresponded to an estimated deficit of about 35 mm. Most of this came from the ridge—possibly nearly all—and once again there is some evidence of the cultivation technique working against the water need of the crop in the first five or six weeks of growth.

## 4. Kale 1967, 1971

**1967.** The results for kale have the same defects as those for sugar beet (Part I) in that plant spacing and leaf structure produce erratic variation in duplicate measurements. In addition, in two out of the three irrigation operations there were faults and errors not detected quickly enough. Those identified were: (1) blocked jets on one line—that which was supplying the area near two access tubes. (2) A spray-line that did not complete its full arc of swing and so watered its two areas unequally. (3) Because the line was not quite high enough above ground, at the horizontal jet extremes of throw the important jet in the system struck the top of a plant and water was diverted from the area around the access tubes. The record is in Table 10(a), showing the measured amounts for three irrigations each nominally 25·4 mm. It is the worst that ever happened.

Variety Thousand Head was grown on the macroplots, with four access tubes at O sites on Mn and four at I sites on Ms. The plant spacing was about 10 cm in rows 56 cm



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TABLE 10(III)

*Kale, 1967. (a) Irrigation distribution (mm); (b) Periodic water balances (mm)*

(a)

| Site: | NE | SE | SW | NW | Nominal |
|---|---|---|---|---|---|
| 6 July | 33·6 | 5·1 | trace | 16·0 | 25·4 |
| 17 July | 26·0 | 26·9 | 25·7 | 11·7 | 25·4 |
| 24 August | 31·3 | 25·1 | 27·7 | 7·1 | 25·4 |
| Totals | 91 | 57 | 54 | 35 | 76 |

(b) Net drying (mm)

| | | NE | SE | SW | NW | $R$ | $E_T$ |
|---|---|---|---|---|---|---|---|
| O sites | | | | | | | |
| 4/7–24/7 | | 43 | 50 | 73 | 57 | 36 | 67 |
| 24/7–25/8 | | 47 | 37 | 30 | 28 | 57 | 72 |
| 25/8–25/9 | | 30 | 29 | 31 | 35 | 43 | 44 |
| 25/9–26/10 | | −81 | −83 | −82 | −72 | 107 | 23 |
| Totals | | 39 | 33 | 52 | 48 | 243 | 206 |
| | | | | | | $\bar{D}_O$ 43 | |
| I sites | | | | | | | |
| 3/7–26/7 | | −1 | 18 | 26 | 38 | 37 | 72 |
| | I | 60 | 32 | 26 | 28 | | |
| 26/7–24/8 | | 26 | 16 | 45 | 11 | 56 | 65 |
| 24/8–11/9 | | −3 | 9 | 7 | 30 | 21 | 36 |
| | I | 31 | 25 | 28 | 7 | | |
| 11/9–26/10 | | −38 | −56 | −80 | −94 | 129 | 36 |
| Totals | | 75 | 44 | 52 | 20 | 243 | 209 |
| | | | | | | $\overline{I + D_I}$ 48 | |

apart, and at the first monitorings (4 and 3 July) the I plants were 30 cm tall and covering 35% of the ground, while the O plants were a little bigger (40 cm; 40%): the leaf area index was then about 2·5. By mid-July the plants were equal on both plots, and thereafter a small detectable difference was in favour of the irrigated crop. By mid-August cover was complete and plants were 100 cm tall and still growing slowly upward, leaf area index reaching 4 in mid-July, and 5 by the end of August.

There were 12 sets of readings at O sites, and 13 at I sites, frequently on different dates. Probably because of the way kale leaves shed rain and irrigation water there was considerable scatter in the measurements of net drying over weekly intervals (first nine periods of Fig. 12, left), more marked when irrigation was applied. On one occasion (10 July, I site SW) the readings were suspect and were rejected, so for the two periods affected (6 to 10 and 10 to 17 July) the average value of $D_I$ is the mean of three values, but all others, O and I, are means of four values.

**Drying by layers (O sites: Fig. 12, left).** The trends in the five 30 cm thick layers show some evidence of conventional 'field capacity' behaviour, in that only the top layer responds to mid-summer rain. The first four layers responded to the heavy rain in October (final period) but the fifth did not. As always, it must be asked whether the drying, 120 to 150 cm, in the last three periods (September and October) represents root action or downward drainage: it is treated as root action, and counts toward the evaporation total in Fig. 13.

**Evaporation and water balance (Fig. 13; Table 10(b)).** The result is to give a slightly increased slope to the trend of points on Fig. 13 over the last three periods (or $E_T$ too small?). Obviously the transpiration rate of the kale was not affected by the absence of irrigation, and from 4 July to 25 September the average deficit at O sites increased by 120 mm, possibly from a value near 10 mm on the first date. The smoothing effects of



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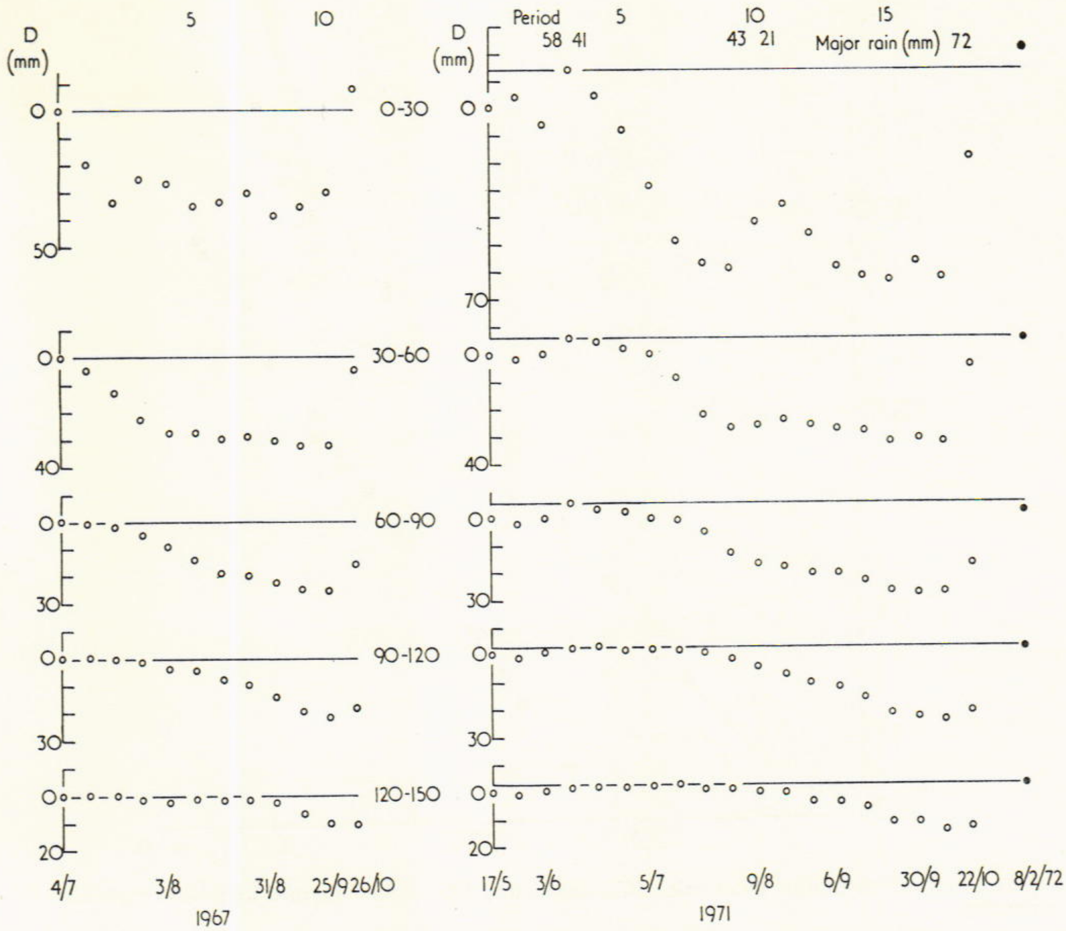


FIG. 12 (III). Drying by layers at O sites, kale 1967 and 1971, on the open scale. Horizontal lines are at maximum summer water content. For 1967, values are averages of 4: for 1971, they are averages of 2 out of 4. Along the top right are values of major rain.

averages, and of time, are clear from the water balances in Table 10(b)—and also the great scatter at I sites in the period 11 September to 26 October. (There were no I site readings on 25 September, as there were for O sites.)

**1971.** The kale (Thousand Head) was again on the macroplots (O sites, Mn; I sites, Ms) with four access tubes in each. There were three irrigations in July, nominal total 76 mm, with no important scatter in the three × four sets of measured amounts that gave seasonal totals of 81·9 (NE), 84·5 (SE), 76·1 (SW) and 79·9 (NW) mm. Nineteen sets of measurements were made from mid-May to late October. At the first (17 May) the crop was 5 cm tall and cover was about 2%. The irrigated crop grew very uniformly, attaining full cover early in July and a height of 100 cm by the end of July, with a slow increase later. In contrast, at the O sites, even before any irrigation was applied elsewhere, growth was less uniform, both height and fractional cover being less at the SE site than at the other three. The absence of irrigation clearly retarded growth in July, and it was early August before O site plants attained full cover, and the end of August before they reached a maximum height of 70 or 80 cm, with no important change later.

There were many anomalies in the estimates of net drying, notably in the SE O and NE I results, even before irrigation, with clear evidence of flooding around the bottom



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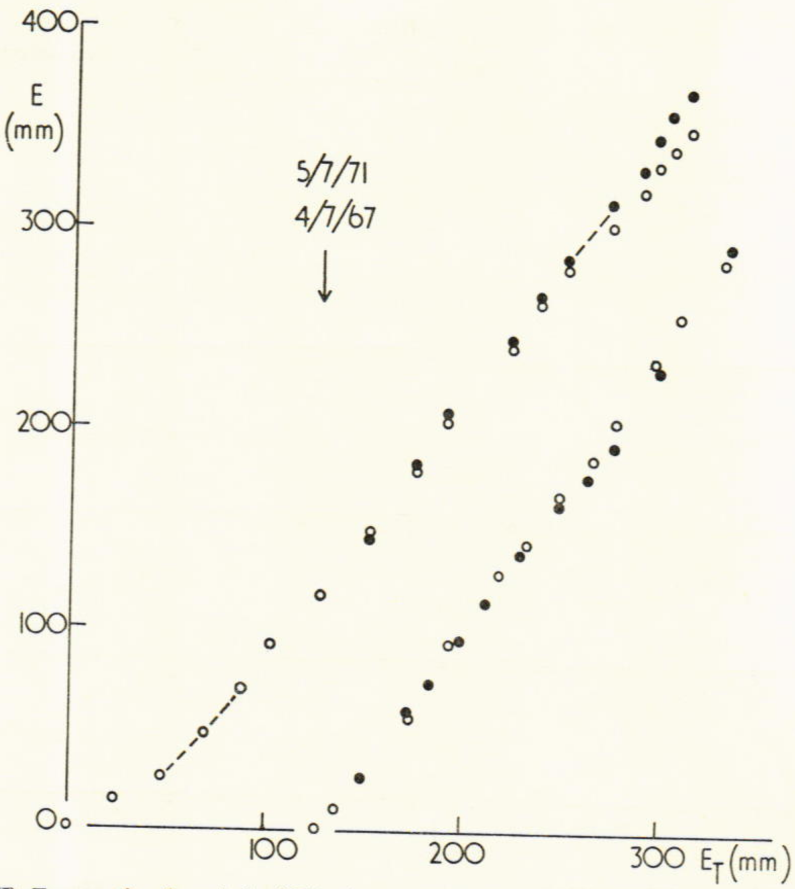


FIG. 13 (III). Evaporation from kale, 1971, above, and 1967, below. Dashed lines show gaps filled by estimates.

of some access tubes, and a strong suspicion of it for others. So the first trial water balance was limited to the depth range 0 to 120 cm, and the SE O and NE I results were excluded. The result did not differ much from Fig. 13, but with a clear difference between $E_I$ and $E_O$, some of it caused by the greater effect of the truncation at 120 cm on the O results than on the I results. The first irrigation was in Period 7, so until then all measurements were on eight replicates of O treatment. Periods 3 and 4 had rain in excess, leaving four (1, 2, 5 and 6) available for a uniformity test. From the eight values of $D$, 0 to 150 cm, for each, values of $\bar{D} \pm e$ were found and gave $e \simeq 4$ mm for a range of $\bar{D}$ from $-$ 3 to 22 mm; in all four periods the value of $e$ was dominated by two values of $| \bar{D} - D |$ of 5 mm or more. Omitting these extremes the re-calculated $\bar{D}$ (6) differed very little from $\bar{D}$ (8), and this was maintained in nearly all later periods when the same exclusion principle was applied in parallel with the null hypothesis. (Over the 14 periods so treated, the accumulated change in $\bar{D}$ was only 6 mm, and the range in individual periods was from + 1·1 to $-$ 2·6 mm, the latter twice in irrigation periods where the change could be a measure of a loss by drainage.) Because the null hypothesis is probably not true in the later periods, the same criterion was used, *as a guide* to quality control on the individual groups of O and I results from Period 7 onward. The result is in Table 11 where entries under $E$ are much too precise for the present purpose. A few periods need comment. In the light of first analyses it seemed reasonable to set $E = E_T$ in Period 3, and 1·15 $E_T$ in Period 4: the inferred average drainage in the two periods is 39 mm, only a little less



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**TABLE 11(III)**

*Kale, 1971. Probable evaporation (mm)*

| | Period | $R$ | $I$ | $E$ O | $E$ I | $\Sigma E_T$ |
|---|---|---|---|---|---|---|
| 1 | 17/5–26/5 | 17 | | 14 | | 23 |
| 2 | 26/5–3/6 | 6 | | 11 | | 47 |
| 3 | 3/6–17/6 | 57 | | $22 = E_T$ | | 69 |
| 4 | 17/6–23/6 | 41 | | $22 = 1{\cdot}15\,E_T$ | | 88 |
| 5 | 23/6–28/6 | 5 | | 23 | | 103 |
| 6 | 28/6–5/7 | 2 | | 25 | | 127 |
| 7 | 5/7–12/7 | 0 | 28 | 30 | 29 | 152 |
| 8 | 12/7–19/7 | 0 | 28 | 33 | 37 | 176 |
| 9 | 19/7–26/7 | 3 | 21 | 24 | 26 | 191 |
| 10 | 26/7–9/8 | 43 | | 36 | $26 = E_O$ | 224 |
| 11 | 9/8–17/8 | 21 | | 23 | 22 | 238 |
| 12 | 17/8–25/8 | 5 | | 18 | 18 | 252 |
| 13 | 25/8–6/9 | 6 | | 21 | $29 = 1{\cdot}3\,E_T$ | 274 |
| 14 | 6/9–16/9 | 0 | | 17 | 17 | 290 |
| 15 | 16/9–23/9 | 0 | | 13 | 16 | 298 |
| 16 | 23/9–30/9 | 13 | | 8 | 11 | 306 |
| 17 | 30/9–11/10 | 1 | | 10 | 11 | 314 |
| 18 | 11/10–22/10 | 72 | | ? | ? | 319 |

than the 45 mm for the potatoes in the same period of 1971. In Period 10, a wet period after three irrigation periods, $D_I$ exceeded $D_O$ in a way suggestive of drainage from the irrigated plots and so $E_I$ was set equal to $E_O$. Period 13 was the most awkward to handle. The values of $D_I$ were erratic (two large, two small) and it was decided to reject them all and use $E_I = 1{\cdot}3\,E_T$ for the period. The last very wet period produced clear evidence of flooding around two access tubes, and strong evidence of it at three or four others. With $E = R + D$ expected to be about 7 mm, the measured values of $R + D$ were: O sites; 7, − 20, − 7, − 6: I sites; − 34, − 1, 2, − 4. The two extreme distortions are for the SE O site and the NE I site, already suspect earlier in the season. For Fig. 13 the record ends with Period 17. The final gap between $E_I$ and $E_O$ is 20 mm. It is thought to be real, and probably too small. The slight divergence begins at about $E_T \simeq 180$ mm, in mid-July, at a soil moisture deficit near 120 mm, about the same as the maximum attained in 1967 when $E_I$ and $E_O$ were not clearly distinguishable.

**Further comment on Figs. 13 and 12.** In combining results for 1967 and 1971 (Fig. 13) those for 1967 start from the value of $E_T$ reached on about the same date in 1971 so that the vertical comparisons are at about the same stage in development. The general slope of both sets of points thereafter is near 1·3.

Fig. 12 is for O sites only, and the right hand part includes a set of results taken on 8 February 1972—with the 'Period' gap widened. The values here are averages for two sites only (SE and SW), simply because in the general—though not severe—scatter of the four sets there were one or two periods when either the NE site or the NW site seemed a little out of step with the other three. The selection in no way distorts inferences from Fig. 12. As drawn, the deficit ($D$, downward) in each layer is calculated from a zero at the first monitoring on 17 May 1971, and at the end of Period 3 (58 mm of rain) all layers had gained water: the horizontal lines drawn are through this early summer water content. In Period 4 (41 mm of rain) the surface layer got drier, but there was little change in the deeper layers, suggesting that at the end of Period 3 all four were at field capacity, and it is interesting to note that, well within observational uncertainty, the four readings on 8 February 1972 agree with the maximum early summer 1971 water content. If, as a result of drying or temperature changes, there was any decrease in the water content at field capacity, recovery during the winter was complete. For the top layer, the February



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water content was 8 mm greater than the wettest in June and this is a fair measure of possible evaporation in the June days between the end of the rain period and the fourth monitoring. The behaviour in Periods 10 and 11 repeats experience in most of the ten years of the measurements, with water getting at least as far as the bottom of the first 30 cm layer: at the end of Period 9 the deficit in the layer was 75 mm below the line and the 43 mm of rain in Period 10 could not have brought it all to field capacity, nor could the weather in the next few days have then produced new drying to the extent of 55 mm evaporation. On this soil, summer rain does not completely re-wet a dry top layer before there is an excess of water to move downward, and there may be implications for the ease and safety of cultivation and harvesting operations soon after summer or autumn rain, and also for nutrient movement and uptake, as in another aspect of both parts of Fig. 12. Again this is true of other crops in other years, that while a top layer is re-wetting, lower layers go on drying. Does this mean that the deepest—and presumably the youngest—roots are the main water collectors for the plant?

**TABLE 12(III)**

*General summary, 1962–71*

| Crop | Year | Depth (cm) | $I$ (mm) | $z_M$ (cm) | $D_O$ (mm) | $E_I - E_O$ (mm) | $\kappa$ |
|---|---|---|---|---|---|---|---|
| Bare soil | 1962 | 90 | 0 | 60 | 40 | — | — |
| | 1963 | 90 | 0 | 60 | 30 | — | — |
| Short turf | 1971 | 150 | 0 | 120 | 95 | — | 1·0 |
| Meadow fescue | 1964 | 90 | 75 | $\geqslant$90 | 75 | <65 | 1·15 |
| Timothy | 1964 | 90 | 75 | >90 | 60 | <65 | 1·15 |
| Winter wheat | 1962 | 90 | 0 | >90 | 95 | — | >1·0 |
| Spring wheat | 1969 | 150 | 110 | 150 | 165 | 0 | <1·3 |
| Spring barley | 1963 | 90 | 0 | 90 | >70 | — | 1·1 |
| | 1965 | 150 | 25 | 90 | >20 | 0 | 1·15 |
| | 1967 | 90 | 115 | >90 | 60 | 40 | 1·2 |
| | 1969 | 150 | 70 | 150 | 130 | 15 | 1·25 |
| | 1970 | 150 | 145 | 150 | 135 | 25 | 1·15 |
| Beans | 1965 | 90 | 15 | — | — | 10 | — |
| | 1966 | 150 | 60 | 90 | >45 | 20 | 1·1 |
| | 1967 | 90 | 120 | >90 | 70 | 40 | 1·0 |
| | 1968 | 150 | 100 | 90 | 50 | 35 | 1·1 |
| | 1970 | 150 | 150 | >90 | 50 | 90 | 1·15 |
| | 1971 | 150 | 80 | >60 | 30 | 50 | 1·2 |
| Potatoes M | 1965 | 90 | 25 | 60 | >25 | 0? | 1·0 |
| M | 1966 | 90 | 25 | 60 | >25 | >0 | 1·05 |
| KE | 1966 | 90 | 25 | 60 | >20 | >0 | 1·05 |
| M | 1968 | 150 | 75 | 60 | 15 | 0 | 1·05 |
| KE | 1969 | 150 | 130 | <90 | 25 | 60 | 1·25 |
| KE | 1971 | 150 | 85 | >90 | 35 | 35? | >1·1 |
| Sugar beet | 1970 | 150 | 130 | 150 | >100 | (40) | 1·3 |
| Kale | 1967 | 150 | 75 | 150 | >120 | 0 | 1·3 |
| | 1968 | 150 | 0 | ? | ? | — | 1·2 |
| | 1971 | 150 | >80 | 150 | 120 | >20 | 1·3 |

Notes on the table

$z_M$ is the approximate maximum depth of drying in unwatered plots
$D_O$ is an estimate of the maximum drying in the profile before there was a detectable check to transpiration
$E_I - E_O$ is the final difference between water use by irrigated and unirrigated plots
$\kappa$ is the slope of the line relating $E$, the estimated actual evaporation, to $E_T$, the estimated potential evaporation, over the main growing period
M = Majestic; KE = King Edward



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## General survey (Table 12)

Without many necessary qualifications, a summary of ten years' results in terms of a few figures for each crop might be misleading, but it is attempted in Table 12, using four indices. Most of this information has already been given in the text, but a little is newly extracted from the records. Based on the 30 cm layers, the quantity $z_M$ is an indication of the depth of root activity and, confining comment to the farm crops, it is clear that for beans and potatoes activity is limited to the top metre of the soil profile but for the other crops it goes to 1·5 m, and that this is the minimum desirable depth of access tube needed. The maximum net drying, $D_O$, is sometimes the value of the deficit under the unirrigated plots at the time when the values of $E_I$ and $E_O$ seemed to diverge, and sometimes the maximum deficit measured at any time in a season when circumstantial evidence suggested that there was no important check to transpiration. Large values of $D_O$ are associated with large values of $z_M$. The final difference in water use, $E_I - E_O = \Delta E$, is usually the value before harvest, is always less than the amount of irrigation applied, and is very often much less. The difference, $I - \Delta E$, represents extra wetting of I site profiles relative to O site profiles, and would appear as an extra contribution to the autumn and winter deep percolation under I sites. Here, on Great Field, this part of the applied irrigation returns to the aquifer from which it was pumped in the first place, and only the part $\Delta E$ is an extra contribution to the atmosphere's water content.

The quantity $\kappa$ is most in need of extended discussion, but this must be deferred until the micrometeorology of the experiments has been considered. At present it is enough to note that for short turf the value is re-assuringly close to unity, that for the hay grasses, barley, beans and potatoes values are near 1·15 and occasion no surprise, but for the spring wheat, sugar beet and kale the values are near 1·3, which are surprisingly large, particularly for the wheat.

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