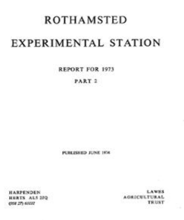
Rothamsted Experimental Station Report for 1973 Part 2


ROTHAMSTED

EXPERIMENTAL STATION

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Rothamsted Weather

H. L. Penman

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Rothamsted Weather

H. L. PENMAN

The purpose of this survey is to give some idea of the physical environment in which Station experiments are done, or have been done. A thorough survey would need an extended discussion of the physics of the inter-relations of the components, but this is not needed now because a former member of the Department, Dr. J. L. Monteith, has set it all out in a book—*Principles of Environmental Physics* (1973)—dealing with both plants and animals.

The starting point was obvious to Swift. During his visit to the scientific academy in Laputa, Gulliver was interested to discover a research worker who 'had been eight years upon a project for extracting sun-beams out of cucumbers, which were to be put into vials hermetically sealed, and let out to warm the air in raw inclement summers'. Swift got his thermodynamics wrong but his agriculture was faultless.

In plant growth we are trying to fix solar energy in a way that makes it usable later and elsewhere, but measurements show that in terms of *total botanical yield* the best of our crops rarely fixes more than about 1% of the solar energy received. As the theoretical maximum is near 10%, the gap presents a big research challenge. Looking at the fate of the other 99%, about 30 or 40% of the income is used in evaporating water, and this almost complete dependence of water use on weather is best considered in relation to the net radiation, which is the balance left after deducting estimated amounts for reflection (*c.* 25%) and net outward long-wave transfers to the atmosphere (*c.* 35%). As expenditure, known sometimes as the 'heat budget', the net radiation income is shared among evaporation, warming the air, and warming the soil. The temperatures attained by air and soil may be important in two ways. First, air and soil are sources or sinks for heat energy—quantitative behaviour. But, secondly and sometimes very importantly, they define a qualitative state of the environment that may determine reaction rates or the vigour of biological activity. Variations of temperature with position and time depend on transport parameters, and in the atmosphere these are determined almost completely by wind and its associated turbulence, above and within the crop, and much of the physics of turbulent transport of heat can be applied, with only minor modifications, to transport of other quantities, to or from the crop. These include momentum (crop movement, and, possibly, lodging), water vapour (imposing a constraint on evaporation rates), carbon dioxide (in photosynthesis) and 'pollutants' (spores, pollen, insects, sprays, dusts . . .). Specification of water content in the air always needs a little care. There are several ways of giving an *absolute* humidity, all acceptable in their appropriate contexts and all of which would support, in numbers, the fact that the atmosphere is drier in December than it is in June. There is one way of expressing *relative* humidity, as a fraction of the amount that the air could hold if it were completely saturated at the prevailing temperature. The associated number never exceeds unity, and it may go through a big daily cycle in summer as the air temperature changes. Its importance lies in the equilibrium conditions it dictates. In terms of relative humidity the daytime atmosphere is wetter in December than it is in June.

Within a farming context the most important transport process is that of evaporation—the water use by crops. The balance of evaporation and rainfall is a major determinant of crop growth, and the frequency of the summer balance being severely unfavourable

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has led to use of irrigation to supplement rainfall. Over the whole year, it is rare for the total evaporation to exceed the total rainfall, so that there is some excess for drainage that is a contribution to the store from which a water harvest is taken out of the chalk aquifer under the farm. Rothamsted climatology is not exclusively agricultural: it has hydrological utility too.

Radiation

Units. In the past, three energy units have been used, and none is obsolete. For internal coherence here the currently least fashionable will be used—the Calory. For conversion:

$$1 \text{ calory} = 4{\cdot}18 \text{ joules}$$
$$= 1{\cdot}16 \text{ mWh (milliwatt hour)}$$

It is sometimes convenient to use a 'working unit' derived from the latent heat of vaporisation of water, which, at ordinary temperatures, is near 590 calories per gram. One gram of water represents a volume of 10 mm × (1 cm)^2, so, as an evaporation equivalent of energy per unit area, 59 cal cm^{-2} is equivalent to 1 mm of evaporation.

Symbols

R_A = theoretical intensity at the outside of the Earth's atmosphere
R_I = measured intensity (short wave)
R_n = net radiation
R_{nD} = net radiation during daylight
R_B = back radiation (long wave)
N = number of daylight hours
n = duration of bright sunshine
m = fraction of sky covered by cloud.

As a good working approximation for a week or longer, but NOT for single days,

$$R_I/R_A = a + bn/N \qquad (1)$$

with

$$a = 0{\cdot}18 \qquad b = 0{\cdot}55 \qquad \text{(Penman, 1948)}$$

revised to

$$a = 0{\cdot}16 \qquad b = 0{\cdot}62 \qquad \text{(Penman, 1970)}$$

Broadly, the first term (a) is a measure of the diffuse light scattered from the sky and clouds, while the second term is a measure of the direct component. Again as a working approximation, during the day n/N is roughly equal to $1 - m$, where m is the average fraction of the sky covered by cloud.

The spectral composition of the light is not detectably dependent on m, and for growth studies it is safe to use:

$$\text{Photosynthetically active radiation} = 0{\cdot}50\ R_I \qquad \text{(Szeicz, 1974).}$$

The reflection coefficient of most fresh green farm crops is near 0·25 (Monteith, 1959). As much of the reflection is in the infra-red region the apparent visible colour is not a safe guide to reflection coefficient.

History. Apart from periods for instrument repairs, solar radiation has been recorded daily at Rothamsted since October 1921. The first instrument was a Callendar recorder, purchased by the Plant Physiology Department of Imperial College in 1916, and run at Rothamsted for the Department from 1921. In 1943 Professor Blackman asked Rothamsted to take over the instrument and be responsible for all future repairs and replacements.

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Right up to 1954 there was great uncertainty about the sensitivity, and as the original supplier had ceased to make them the replacement then sought had to be found elsewhere. Over the first 30 years the readings were probably accurate enough for the use that could be made of them *at the time*, but as they are not good enough for present needs they are not considered here.

In 1955 a Moll-type solarimeter (Kipp) was installed with a paper chart recording potentiometer. As before, daily totals were obtained by planimeter integration—a tedious and awkward task—until in 1958 an automatic integrator was added with a digital counter set to register directly in cal cm^{-2}. Read every morning, the change in counter readings is the required total income for the previous day. The entries in Table 1 are for the Kipp instrument: the numbers are too precise and should be read against the possibility of a 2% error.

The easier recording of hours of bright sunshine started in 1892. A glass sphere acts as a burning glass and produces a brown scorch mark on a suitably sensitive blue card graduated in hours. The length of burn is measured to the nearest tenth hour for every hour, and noted. Addition gives the daily total. There are several recognised sources of error, but observers work to a set of rules in reading the cards and totals are probably accurate to about 1%.

Net radiation is not yet a routine weather element, but as it is the main determinant of rate of water use it has been measured—using our own construction of instruments—as a research exercise since 1955. The observations have not been sufficiently continuous over long enough periods to display mean values acceptable as climatic averages. In general, net radiation is *negative* from shortly before sunset to shortly after sunrise, markedly so on clear nights (Fig. 1), and in the short winter days the 24-hour total is negative. The summer balance is always positive with $R_n/R_I \simeq 0{\cdot}5$ for the whole day, and $R_{nD}/R_I \simeq 0{\cdot}6$ for daylight hours (Table 3).

Solar radiation: Daily cycle (Fig. 1). The curves on the left are for almost clear days and nights, with totals in the inset table. *Almost* is important. In the record for 23 June both the peaks and the troughs are probably the result of light cumulus cloud, obscuring the sun to produce the troughs, and providing extra scattering from the sky to produce the

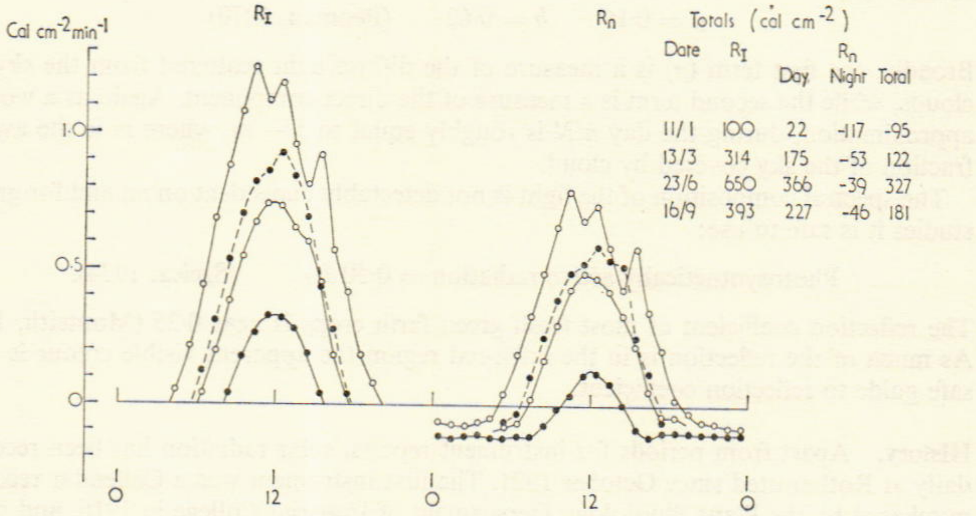

FIG. 1. Solar radiation (left) and net radiation (right) over grass on almost cloudless days, 1961. In descending order, the dates are: 23 June, 16 September, 13 March and 11 January. Night detail for March and September (right) is omitted from the figure but included in the totals. (From G. Szeicz.)

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peaks. The day's total, at 650 cal cm^{-2} exceeds what would have been obtained with no cloud, and is the greatest recorded since 1955.

TABLE 1

Rothamsted: Solar radiation: Average daily totals (cal cm^{-2})

	J	F	M	A	M	J	J	A	S	O	N	D	Year
R_A (Angot)*	192	336	525	750	932	1010	979	825	619	398	241	163	
Measured R_I 1956–59 (4)	61	112	207	299	396	414	377	308	233	138	63	36	220
1960–64 (5)	52	97	162	252	369	431	365	310	237	131	59	42	209
1965–69 (5)	49	85	188	268	345	409	358	291	213	124	59	33	202
1970–72 (3)	37	86	182	243	383	392	355	298	238	140	68	35	205
Average (17) Cal cm^{-2}	50	95	190	265	370	415	365	300	230	130	60	35	210
Equiv. E (mm)	0·8	1·6	3·1	4·5	6·3	7·0	6·2	5·1	3·9	2·2	1·0	0·6	

* For latitude 52° N. Solar constant = 2·00 cal cm^{-2} min^{-1}

Annual cycle (Table 1, Fig. 2). The 17-year record is split into four periods in a way that makes it possible to pick out the decade 1960–69 for comparison with entries in other tables. At the top are given the values of the income there would be if there were no atmosphere. The values have been estimated by a double interpolation of R_A in a table in the 1951 edition of the Smithsonian Tables, and adjusted to conform to a more recent estimate of the solar constant. At the bottom the long-term daily averages of R_I have been converted to daily evaporation rates if all the sunshine was used in vaporising water.

Fig. 2 gives the mean values for the decade 1960–69, as discrete points.

Duration of bright sunshine (Table 2). Except for 1894 when some records were incomplete, all the available measurements are summarised, with a few supplementary

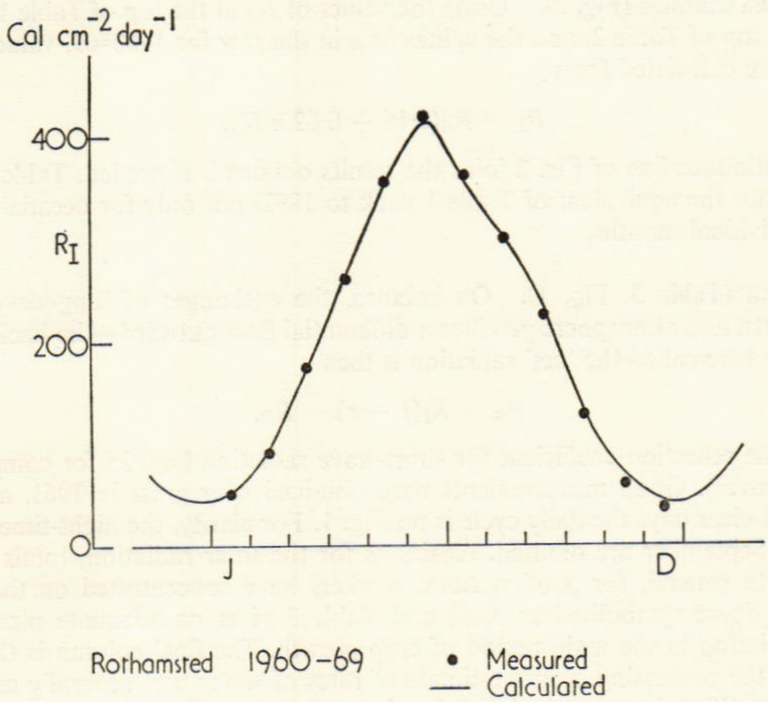

FIG. 2. Average monthly solar radiation for a ten year period (full points). The line joins calculated values (Equation 2).

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TABLE 2

Rothamsted: Hours of bright sunshine: Monthly averages per decade

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Max. poss. (N)	257	280	362	393	492	498	499	452	378	332	261	239	4443
1892–99*	43	72	122	167	205	203	213	207	161	111	56	46	1608
1900–09	62	72	113	173	197	195	228	204	158	101	63	42	1607
1910–19	47	65	101	158	209	208	173	171	153	101	69	39	1494
1920–29	53	70	125	140	212	207	198	175	148	116	68	50	1563
1930–39	52	76	134	131	169	206	184	187	135	103	57	41	1475
1940–49	55	64	114	168	198	201	185	180	132	99	61	51	1507
1950–59	55	65	114	161	189	195	190	167	137	102	57	42	1475
1960–69	48	59	109	128	175	203	165	155	132	93	54	48	1371
1970–72†	36	70	113	112	198	184	179	155	147	114	74	36	1419
Year													
Most (1929)	40	67	185	155	261	226	244	197	206	120	78	75	1854
Least (1968)	38	44	134	170	145	152	136	112	107	56	29	27	1149
Month													
Most	88	106	206	271	280	288	316	271	223	154	104	76	
	1952	1939 1970	1907	1893	1922	1957	1911	1947	1911	1921	1923	1961	
Least	23	22	59	85	124	116	91	99	84	56	26	16	
	1898	1940	1960	1966	1898	1923	1965	1912	1936	1968	1962	1969	

* 7 years: 1894 omitted
† 3 years

items. In the top line are the values of N for each month, averaging just over 12 hours per day in the year's total. Immediately under the main table are rows of extreme values, first the sunniest and least sunny civil years (1929 and 1968), and then corresponding information for individual months.

Radiation and sunshine (Fig. 2). Using the values of R_A at the top of Table 1, the values of N at the top of Table 2, and the values of n in the row for 1960–69, values of R_I for 1960–69 were calculated from

$$R_I = R_A(0{\cdot}16 + 0{\cdot}62\, n/N), \qquad (2)$$

and the continuous line of Fig. 2 joins the results obtained. If needed, Table 2 could be converted into the equivalent of Table 1 back to 1892, not only for decadal means but also for individual months.

Net radiation (Table 3, Fig. 1). On balance, the exchanges of long-wave radiation between Earth and atmosphere produce a differential flow outward—the back radiation, R_B. What is here called the 'net' radiation is then

$$R_n = R_I(1 - r) - R_B, \qquad (3)$$

where r is the reflection coefficient for short-wave radiation ($\simeq 0{\cdot}25$ for complete green farm crop cover). Good measurements were obtained over grass in 1961, and for the four selected clear days the daily cycle is on Fig. 1. For clarity, the night-time values for March and September are omitted. Again, as for the solar radiation, totals are in the inset table. In general, for good reasons, workers have concentrated on the day-time value of R_n (here symbolised as R_{nD}) and Table 3 gives an adequate picture of the seasonal variation in the main period of crop growth. The final column is the primary objective of the processing, a first estimate of rates of water use, generally as an upper limit to be modified downward when other factors are brought into account.

For interest: plotting hourly values of R_n against the corresponding values of R_I on

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TABLE 3

Mean monthly solar and net radiation (daylight hours) over grass, Rothamsted, 1961

Month	Days of record	R_I Cal cm^{-2} per day	R_{ND} Cal cm^{-2} per day	R_{ND} Equiv. E (mm)
April	24	245	150	2·5
May	25	400	219	3·7
June	29	430	264	4·5
July	18	389	222	3·8
August	27	345	205	3·5
September	25	243	140	2·4

Fig. 1 (four sets of measurements) gives a very good straight line with little scatter. The slope is 0·75 (hence $r = 0{\cdot}25$ in equation 3), and the intercept at $R_I = 0$ is $-0{\cdot}11$ cal cm^{-2} min^{-1} ($= -R_B$ for clear skies). The seasonal constancy of the reflection coefficient was not unexpected; the constancy of the back radiation was a surprise.

Canopy interception. For all weather elements considered later, display will be limited to what happens above or below the crop. Behaviour within the crop is too complex for general summary because of variation with height, with time of day, with stage of growth and with the nature of the crop. The exception, on Fig. 3, shows what is perhaps

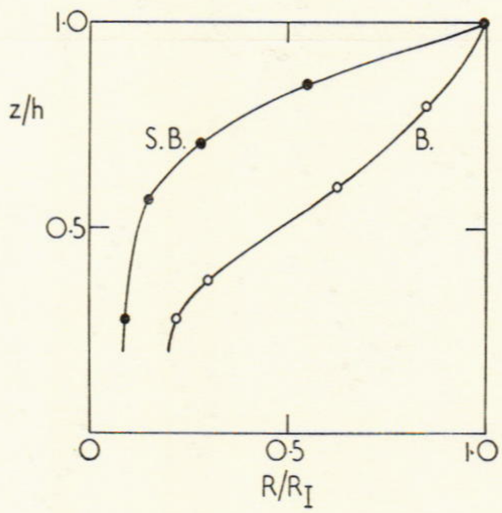

FIG. 3. Light penetration into canopies of sugar beet (27 August 1965) and barley (17 July 1963). (From G. Szeicz.)

the most important effect of the nature of the crop, the extent to which sunshine penetrates a crop canopy. Results are for full stands of sugar beet and barley, averaged over a period of 10 daylight hours. The quantities plotted are the ratios, measured income at z/income at the top of the crop (height h), and z/h. The sugar beet intercepts much more radiation near the top of the canopy.

Temperature

Units and scales. There are two units and three scales, related as intervals by

$$1^\circ \text{ Celsius} = 1^\circ \text{ Absolute or Kelvin} = 9/5^\circ \text{ Fahrenheit}$$

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The ice and steam points on the three scales are

0°C,	273°K,	32°F
100°C,	373°K,	212°F

Until 1970 nearly all temperatures were measured in °F (a few soil temperatures were in °K). Until 1971 the returns to the Meteorological Office continued to be in °F, but were converted there to °C. By 1 January 1972 all our thermometers were replaced, and since then all our records and returns have been in °C.

For the present note most of the records have been used as they were taken, so one table has entries in °F. On diagrams a change of scale is easy, and temperatures are in °C.

Air temperature

Daily variation. Air temperature depends on the temperature of the ground surface, the source of the air (and the vigour of mixing) and on radiation exchanges in which cloud cover can be dominant. Except in winter—and ignoring special cases—a clear day produces high air temperatures (greater input from sunshine) and a clear night produces low air temperatures (greater negative component in net radiation). Something of the sort is on Fig. 4 where the daytime range is from about 25°C to 10°C on 15 July 1971.

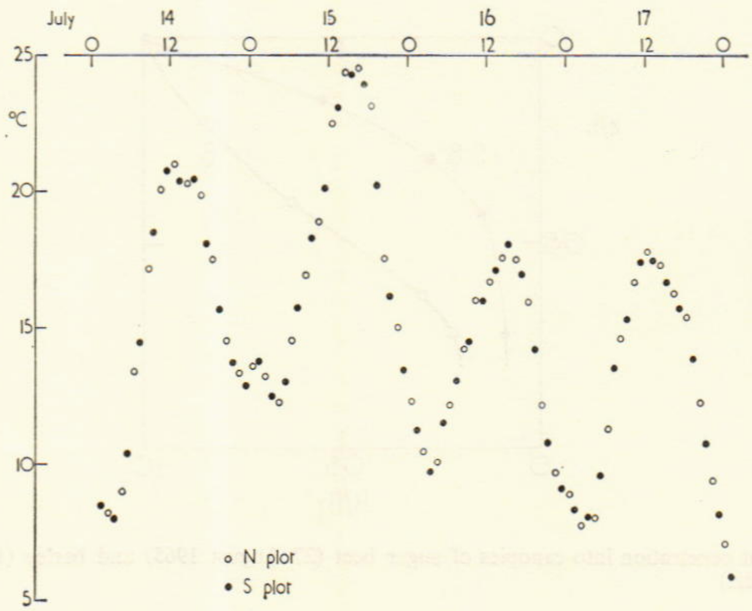

FIG. 4. Air temperature (hourly averages) at about 2 m above a kale crop in fine weather, July 1971. Points are given alternately for two sites about 100 m apart. See also Figs 17 and 19. (From I. F. Long.)

Agriculturally the most important time for this kind of behaviour is early in the growing season, when the clear night plunge may go below freezing point. In cloudy or overcast periods the daily range is smaller, but the start of the daytime rise, however small, is usually detectable at sunrise: the maxima are lower, and the minima are higher. Comparison of 14 and 15 July (Fig. 4) shows the kind of effect, with evidence of cloud thickening for a few hours before dawn on 15 July.

In winter, sunshine is too feeble to have much effect anyway, and the dominant factor is the source of the air. For most of the time it is the Atlantic Ocean, but there are

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occasions of influx of Arctic air from the north, or of continental air from the south-east, the latter sometimes bringing blizzards of snow.

The air temperature can be recorded continuously by a thermograph, and a record will appear later (Fig. 21), but the illustration in Fig. 4 is taken from one of the research projects. The site of the irrigation experiment is alongside the meteorological enclosure and two large plots, each about 100 × 100 m, are instrumented to give frequent temperature (and other) readings at several heights above the crop, within the crop and in the soil beneath. On Fig. 4 hourly averages over kale are plotted alternately for each of the two sites, i.e. 0–1, 2–3, 4–5 for one, 1–2, 3–4, 5–6 etc., for the other. On the scale of the diagram, there are no major discrepancies: over this period of four days there was only a very small horizontal gradient of temperature between two sites about 100 m apart, at a height of 270 cm (about 2 m above the top of the kale plants). For a typical fine summer day of intermittent sunshine and broken cloud, the record on 14 July carries the main features: a rise to a maximum reached an hour or so after noon, no great change for the next 2 hours, and then a fall that continues through sunset until sunrise next day.

Over a long period the true mean air temperature, integrated over the day, differs very little from the mean of the average of maxima and minima, and in all that follows 'mean air temperature' is the average of maxima and minima. For a year, the error may be 0·10°C over-estimate.

Secular change in annual mean (Fig. 5). The values plotted, from 1878 to 1972, are the means of the 12 monthly averages for the calendar year. Within the points are horizontal lines, each spanning 10 years, drawn at the 10-year average. There is a slight, but clear, increase in the decade means up to 1940–49, and a decrease thereafter. The same trend occurs in the records at Kew Observatory (Brazell, 1968), where measurements started in 1871. For the decade 1871–80 the Kew mean is almost the same as that for 1901–10, with a relatively big drop 1881–90, and from 1880 the Kew and Rothamsted 10-year averages run parallel, with Kew about 1°C warmer. Boyd (1939), using earlier Oxford and Greenwich records, gave a usable indication of mean Rothamsted air temperatures back to the beginning of the experiments.

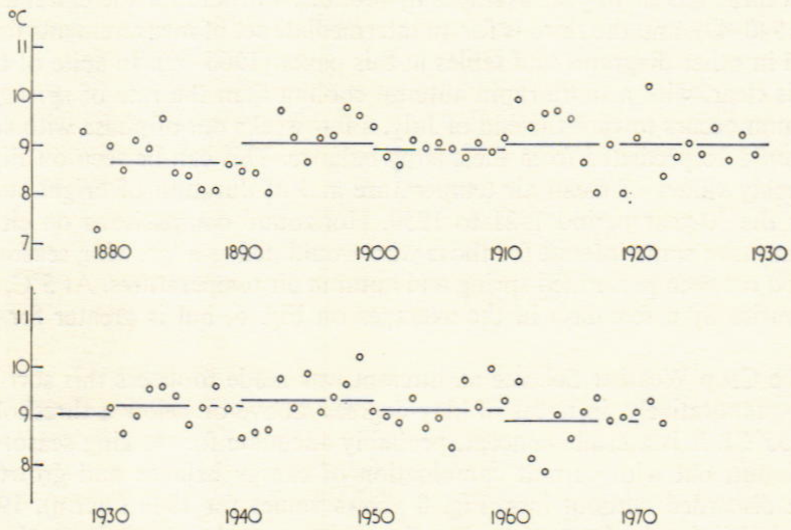

FIG. 5. Mean annual air temperature in the screen, 1878–1972. Horizontal lines show averages for ten-year periods.

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TABLE 4

Rothamsted: Air temperature: Monthly extremes (°F)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Two coldest years													
1879 Max.	34·7	41·6	47·1	49·5	55·3	63·7	63·9	66·2	62·2	53·3	43·0	36·1	51·4
Min.	25·1	33·3	33·4	35·7	39·1	48·8	50·2	52·2	47·2	41·7	32·9	25·1	38·7
Mean	29·9	37·5	40·3	42·6	47·2	56·3	57·1	59·2	54·7	47·5	38·0	30·6	45·1
1963 Max.	30·9	33·6	48·3	54·9	59·0	66·8	68·0	65·6	62·9	56·9	51·2	39·7	53·1
Min.	21·0	24·2	35·3	39·3	41·7	49·1	49·3	49·2	47·4	44·5	40·2	30·0	39·3
Mean	25·9	28·9	41·9	47·1	50·3	57·9	58·7	57·4	55·1	50·7	45·6	34·9	46·2
Two hottest years													
1921 Max.	48·8	45·2	51·8	55·2	62·0	67·4	76·8	69·2	67·6	63·6	43·9	47·9	58·3
Min.	39·7	34·0	36·4	37·3	43·3	47·5	53·4	52·7	49·0	46·4	33·3	36·7	42·5
Mean	44·3	39·6	44·1	46·2	52·6	57·4	65·1	60·9	58·3	55·0	38·6	42·3	50·4
1949 Max.	45·9	48·5	46·6	58·7	60·0	68·3	74·3	72·8	71·1	60·3	48·7	46·5	58·5
Min.	34·6	32·9	32·9	40·3	41·3	47·8	52·5	52·4	54·0	45·7	36·6	36·0	42·2
Mean	40·3	40·7	39·7	49·5	50·7	58·1	63·4	62·6	62·5	53·0	42·7	41·3	50·4
Highest maximum (monthly average)													
	49·0	50·0	57·4	63·1	66·2	71·0	76·8	75·9	72·0	63·6	53·2	49·9	
	1916	1914	1938	1893	1947	1893 1957	1921	1911	1929	1921	1913	1912	
Lowest minimum (monthly average)													
	21·0	20·6	28·4	32·6	39·4	44·9	48·9	48·6	44·8	36·2	31·0	24·2	
	1963	1895	1883	1917	1902	1916	1907	1887	1912	1888	1923	1890	
Peak or trough values in periods above													
Hottest day	54	56	65	77	86	86 89	88	92*	85	79	58	56	
Coldest night	2†	2·5	19	25	28	36	40	40	31	26	12	7	

* Highest ever (and in August 1932)
† Lowest ever

Annual cycle (Fig. 6, Table 5). As a supplement to Fig. 5, but useful in its own right, Fig. 6 gives three sets of 10-year averages by months. Two are for the extremes of Fig. 5 (1880–89, 1940–49), and the third is for an intermediate set of measurements for a decade represented in other diagrams and tables in this paper (1960–69). In spite of the scatter, the shape is clear, with a more rapid autumn cooling than the rate of spring warming. The maximum occurs toward the end of July, a few weeks out of phase with solar radiation—as would be predicted from the energy balance. This can be seen on Fig. 7 where average weekly values of mean air temperature and of duration of bright sunshine are plotted for the 30-year period 1921 to 1950. Horizontal comparisons on either Fig. 6 or Fig. 7 can have some interest for those who would define a 'growing season' in terms of the period between prescribed spring and autumn air temperatures. At 5°C, the spring threshold varies by a few days in the averages on Fig. 6, but is greater for individual years.

Under the Crop Weather Scheme an attempt was made to assess this sort of thing a little more quantitatively, in terms of 'day-degrees' above or below a threshold guessed at 42°F (5·55°C). It is a crude concept, probably adequate for ranking seasons in order of energy input, but with current combination of energy balance and growth analysis it could be discarded without loss. Fig. 8 shows values for 1949 (warm), 1958 (about average) and 1963 (cool). As routine, the values are summed each week: on the figure the weekly totals are summed at four-week intervals.

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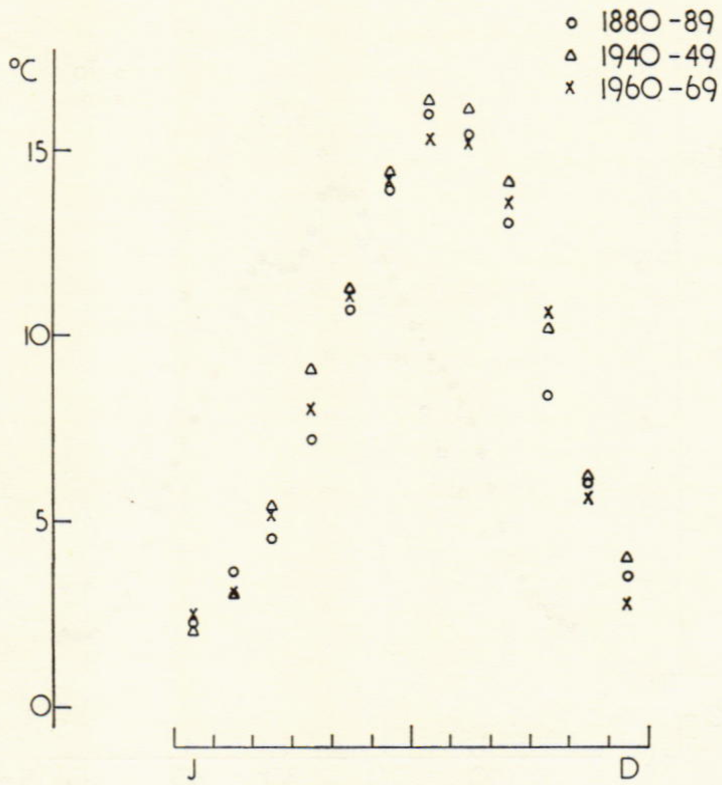

FIG. 6. Annual cycle of average monthly air temperature for decades selected from Fig. 5.

Frost. The slopes of lines such as those of Fig. 8 can be used as guides to growth rates, but *what* we can grow depends on a more important threshold temperature. There are two 'frost' temperatures, that in the screen at about 4 ft above ground, and that at ground level with the thermometer fully exposed to the sky. The thermometer bulb is set at 2 in. above ground carrying mown turf, and the reading is sometimes called the 'grass minimum'. Conventionally, the threshold was defined as 30·4°F on the assumption that no physiological damage would occur above this temperature, and in the older records 'ground frost' means an occasion when the grass minimum temperature was 30·4°F or lower. Now, and here throughout, for several good reasons, convention is ignored, and the specification of 'frost' is any occasion when the temperature is below 32°F. Because of varying precision in the records this produces some slight anomalies, most of which are removed by grouping frequency of occurrence into ten-day periods. On Fig. 9 all 58 records are used for the screen frost, but the record for 1921 is omitted from the surface frost. Statistical analysis of the distribution in the surface frost histograms might show some measurable probability of an overlap: this, in fact, happened in 1921, when there were three ground frosts in June, one in July, one in August, and two in September. (The summer of 1921 was unique. From 1 June to 10 September there were only 1·4 in. of rain, and the occurrence of summer frosts is almost certainly attributable, in part, to the very dry surface soil.) For our farming (and gardening) the surface frost is rather more important than the air frost. The way the information has been assembled makes the description a little unkind to the climate. On average the surface frost-free period is from day 147 (27 May) to day 277 (4 October), an interval of 130 days, with a hint that lengthened intervals are longer at both ends, and shortened intervals are shorter at both ends. In eight years with the last spring frost day in the range 120–129 (average 125)

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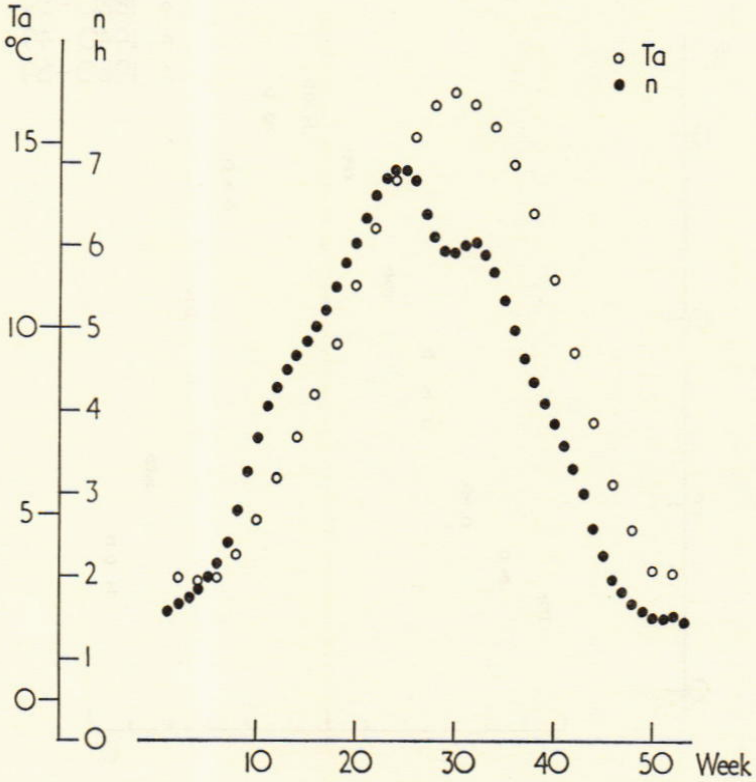

FIG. 7. Annual cycle of average weekly air temperature (open circles) and daily duration of bright sunshine (full circles), 30 years, 1921–50. Points for air temperature are at two week intervals.

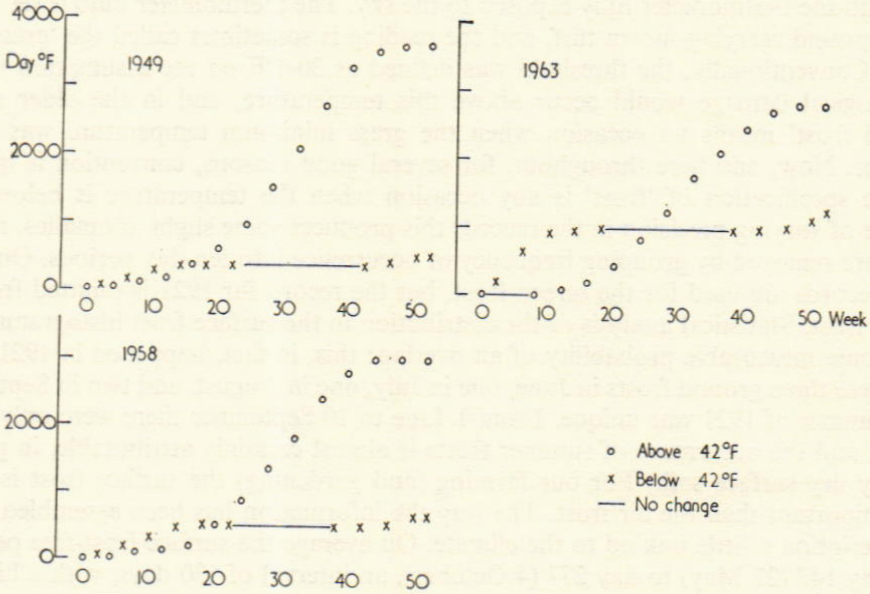

FIG. 8. Accumulated temperature, at four week intervals, for a warm year (1949), a cool year (1963) and an 'average' year (1958).

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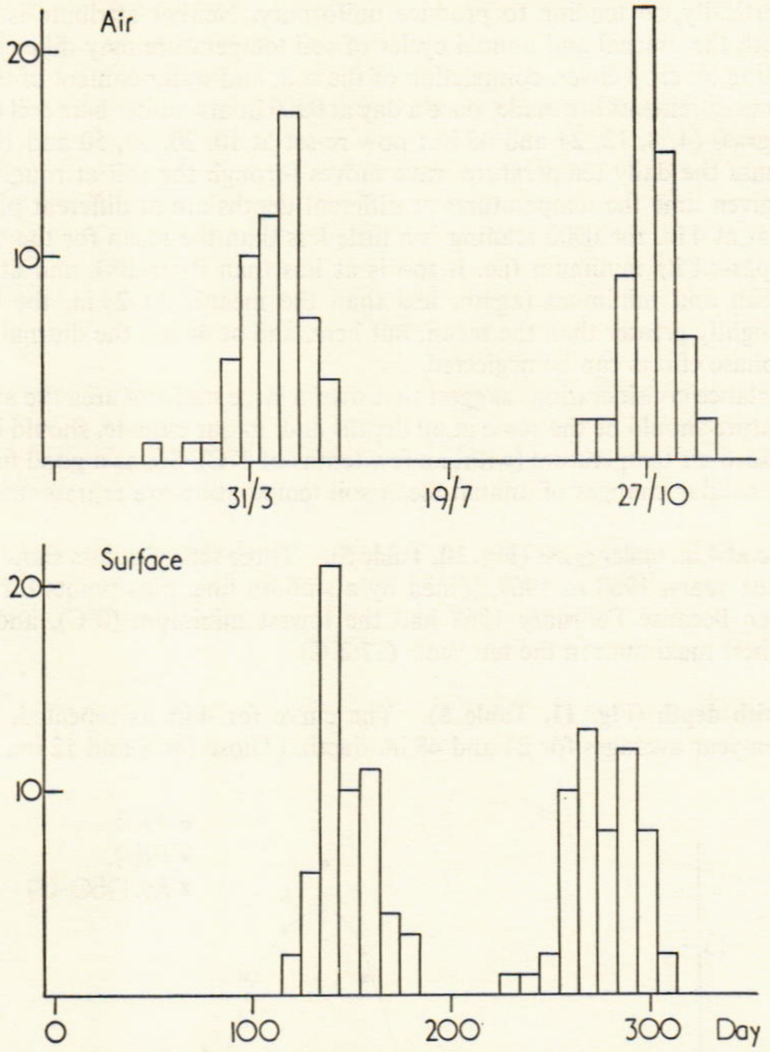

FIG. 9. Air (in screen) and surface (grass minimum) frosts. The columns are ten days wide and their heights (scale on left) give the numbers of years when the last spring frost and first autumn frost occurred in the chosen ten day period. Period: 1915–72 (58 years, but excluding 1921 for surface frosts).

the average first autumn frost day was 286 (interval 163 days): in four years with the last spring day in the range 172–180 (average 176) the average first autumn day was 266 (interval 90 days). Working backward from the autumn, six years in the range 300–310 (average 303) had an average last spring frost day of 138 (interval 165 days), and eight years in the range 234–259 (average 251) had an average last spring frost day of 157 (interval 94 days).

Extremes in air temperature (Table 4). To show what can happen within the average values shown on the diagrams, Table 4 gives the components in the two coldest years, and in the two warmest years, then the largest maximum and smallest minimum for each month, and, within these months the hottest day and the coldest night.

Soil temperature

To an acceptable accuracy, the air temperature as measured in the meteorological enclosure is the air temperature of the neighbourhood: the air moves horizontally and

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is mixed vertically, so tending to produce uniformity. Neither attribute is true of the soil, and both the diurnal and annual cycles of soil temperature may differ from site to site, depending on crop cover, compaction of the soil, and water content of the soil.

Routine measurements are made, once a day at 0900 hours, under bare soil (4, 8, 12 in.) and under grass (4, 8, 12, 24 and 48 in.: now re-set at 10, 20, 30, 50 and 100 cm since 1972). Because the daily temperature wave moves through the soil at roughly 1 in. per hour, at a given time the temperatures at different depths are at different phases of the cycle, so that at 4 in. the 0900 reading is a little less than the mean for the day, at 8 in. it has just passed its minimum (i.e. it too is at less than its mean), and at 12 in. it is between mean and minimum (again, less than the mean). At 24 in. the 0900 hours reading is slightly greater than the mean, but here, and at 48 in., the diurnal range is so small that phase effects can be neglected.

Energy balance considerations suggest that over a large uniform area the annual mean soil temperature should be the same at all depths and, in our climate, should be the same as annual mean air temperature (within a few tenths of 1°C). So, as a good first approximation, the secular changes of annual mean soil temperature are represented by Fig. 5.

Annual cycle at 4 in. under grass (Fig. 10, Table 5). Three sets of points show the average values for ten years, 1960 to 1969, joined by a smooth line, plus points for two of the years, chosen because February 1968 had the lowest minimum (0°C), and July 1969 had the highest maximum in the ten years (17·2°C).

Variation with depth (Fig. 11, Table 5). The curve for 4 in. is repeated, with corresponding ten-year averages for 24 and 48 in. depth. (Those for 8 and 12 in., not shown,

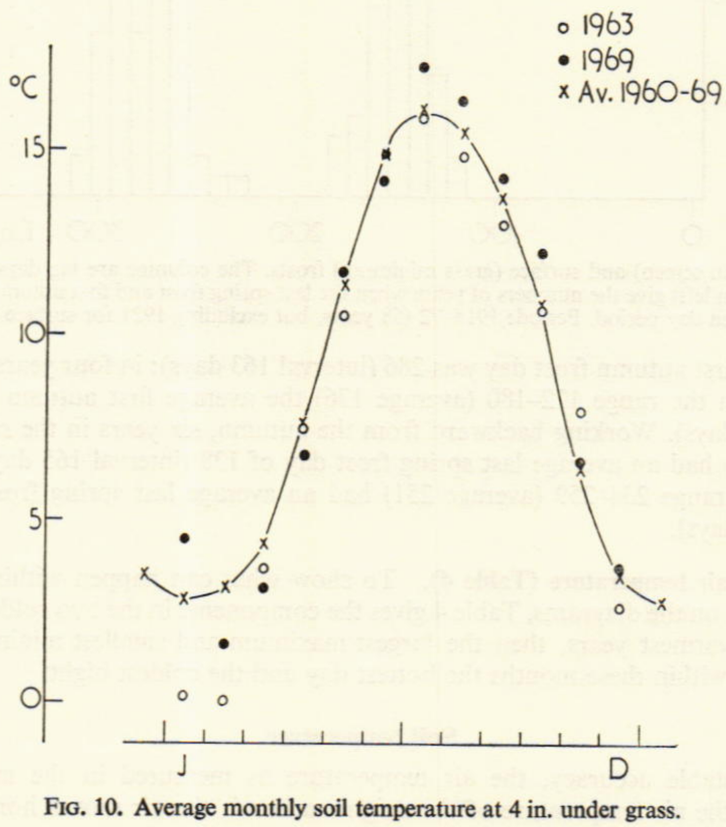

FIG. 10. Average monthly soil temperature at 4 in. under grass.

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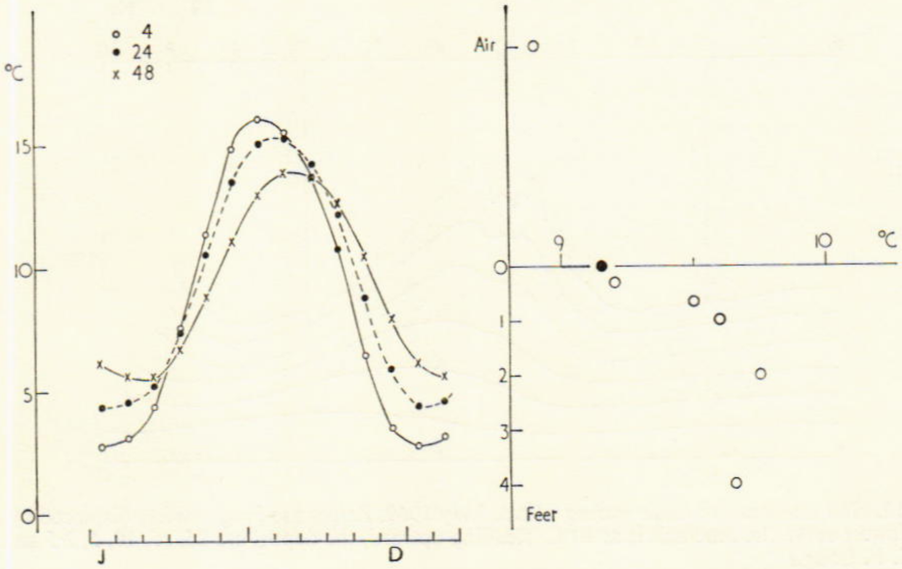

FIG. 11. *Left.* Average monthly soil temperature (1960–69) at three depths (inches) under grass. *Right.* Mean annual soil temperature at five depths, and mean air temperature in the screen—all open circles. The full circle is a calculated value for the surface.

come too close to that for 4 in. to be clearly distinguished: they show the same trends of decreasing amplitude and delayed phase with increasing depth.) Very roughly, the phase lag between 4 and 48 in. is about one month: the velocity of penetration of the annual wave is near $1\frac{1}{2}$ in. per day.

Table 5 gives annual and monthly means for the ten years 1960–69, and on the right of Fig. 11 are the ten-year means plotted against depth. Combining the two sets of information on the figure, and adding a value of the specific heat of the soil, it is possible to infer the following: (1) the average temperature gradient is near 1·5°C m^{-1} in the top 8 in. of the soil; (ii) the thermal diffusivity between 4 and 24 in. is near $2{\cdot}5 \times 10^5$ cm^2 $year^{-1}$; (iii) the upward heat flux is near $2{\cdot}4 \times 10^3$ cal cm^{-2} $year^{-1}$; (iv) for this same flux in the air the temperature difference between soil surface and air at screen level is near 0·25 r_a°C, where r_a is the average resistance to the transfer, and known to be near

TABLE 5

Rothamsted: Mean monthly air and soil temperatures under grass (°C: 1960–69)

	Air	in. 4	8	12	24	48
J	2·5	2·8	3·1	3·4	4·4	6·1
F	3·0	3·2	3·5	3·7	4·5	5·6
M	5·2	4·5	4·8	4·9	5·2	5·6
A	8·0	7·6	7·8	7·8	7·4	6·7
M	11·0	11·4	11·4	11·1	10·5	8·8
J	14·2	14·9	14·7	14·6	13·5	11·1
J	15·3	15·6	16·0	15·9	15·1	13·0
A	15·2	15·5	15·7	15·7	15·3	13·9
S	13·6	13·7	14·1	14·2	14·3	13·7
O	10·6	10·8	11·4	11·6	12·2	12·6
N	5·6	6·4	7·1	7·5	8·8	10·4
D	2·8	3·5	4·1	4·5	5·9	8·0
Year	8·9	9·2	9·5	9·6	9·8	9·6
Highest (1961)	9·7	9·6	9·9	9·9	10·2	10·1
Lowest (1962)	8·2	8·3	8·7	8·8	9·0	9·0

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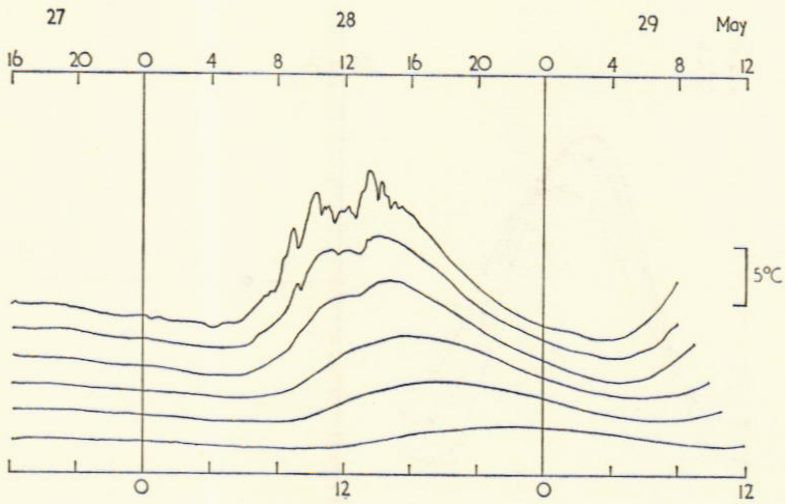

FIG. 12. Soil temperature under spring wheat, May 1969. Zeroes are progressively displaced by 2·5°C: for the lowest curve the time axis is at 10°C. Reading upward, the depths are 25, 15, 10, 5, 2·5 and 0 cm. (From I. F. Long.)

1 sec cm^{-1} or less. Putting $r_a = 1$ leads to the full point plotted at zero depth: the system is coherent.

Daily cycle. There are no routine observations, but, as part of the research, soil temperature is recorded at several depths, closely spaced near the surface and further apart deeper in the profile. The sensors cannot be installed until most farming operations are complete and hence the records are for soil with some crop cover. For illustration, Fig. 12 shows the temperature changes on a fine day, cloudy near noon, after a dull day. The crop was spring wheat, then about 40 cm tall and covering 60% of the ground surface, and the curves, traced from the original record, are for depths 0, 2·5, 5, 10, 15 and 25 cm, with zeros progressively displaced by 2·5°C to avoid confusing overlap. (The run-in from 27 May is left longer than necessary: in this period all temperatures were about the same and near 12·5°C at midnight.) Detail in the upper two curves is very approximate, but important inferences about changes with depth are not affected. First, the rapid fluctuations are soon damped out: second, the amplitude decreases: third, the phase lag increases. Roughly, from the phase lag, the velocity of the daily wave is about 3 cm per hour and—less certainly on this evidence—the crop is behaving as though it represented the equivalent of about 4 cm of soil as a thermal resistance.

Rainfall

Amounts are always expressed as a depth of water, obtained by dividing a measured volume of catch by the area of the collecting surface. For brevity, the diameter of the gauge is used in description (e.g. 5-in., 8-in.). A 5-in. gauge was used in the garden of Rivers Lodge from 1852 until about 1880: the water collected was carried across to the laboratory, the volume measured in a graduated cylinder, and the depth calculated and entered to five significant figures, even when qualified by 'some spilt'! The gauge was moved to the meteorological enclosure, and an 8-in. gauge was installed in 1900(?) and used until 1947. An automatic syphon gauge (6-in.) was added later, giving records of time and intensities. In 1851 Lawes and Gilbert set up a very large gauge with a collecting area of 1/1000 acre, to get enough rainwater for chemical analysis. This pioneer effort in rainfall chemistry showed there wasn't much in rainwater to affect plant growth.

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Much later we added a rain collector for DSIR as part of the national monitoring system for atmospheric pollution (mainly sulphur dioxide and solids), and for a few years we were one of the six sites in Britain taking part in an international study of rainfall chemistry as a guide to the dynamics of movement of weather systems. Results are in volumes 7–12 (1955–60) of *Tellus*, and give values of: amount of rain, its pH and electrical conductivity, and the content of S, Cl, NO_3-N, NH_3-N, Na, K, Mg, Ca and HCO_3^-.

In the 1/1000 acre gauge the volume was measured in a series (4) of tanks each holding the equivalent of ½ in., with external gauge pipes—for direct reading—cemented into sockets. Round about 1943 there was concern about discrepancies between the 1/1000 acre totals and the daily amounts as measured on 5- and 8-in. gauges, and a thorough piece of detective work by Michael Garrod, a student worker, revealed that the cement had softened a little and the first gauge glass had slipped down (over-estimate of amount), and that the first gauge glass itself was incorrectly graduated (again in the sense of over-estimating amount). The fourth glass (for 1·5–2·0 in.) was exchanged with the first, correctly set, and daily readings after 1947 should be more trustworthy than those for a few years before.

The discrepancy could be caused by an under-estimate in the small gauges. This is known to happen in exposed situations, and the Meteorological Office recommendation of 30 years or so ago was to set the gauge (12 in. high) at the centre of a circular turf wall (also 12 in. high), inside radius 5 ft, with a vertical inside face, and a sloping outside face at a slope of about 1 in 5. We set up a 5-in. gauge in this way in 1948, and Table 6

TABLE 6

Rothamsted: Comparison of rain gauges: Ten-year averages, 1960–69

	1/1000 acre	5-in.	5T*	
	n.	in.	in.	mm
J	2·30	2·18	2·22	56
F	1·86	1·75	1·81	46
M	1·81	1·73	1·77	45
A	2·31	2·19	2·24	57
M	2·30	2·21	2·22	56
J	2·30	2·21	2·24	57
J	2·50	2·40	2·42	61
A	2·43	2·29	2·30	58
S	2·69	2·56	2·57	65
O	2·66	2·53	2·53	64
N	2·72	2·59	2·63	67
D	3·00	2·83	2·89	74
Year	28·88	27·47	27·83	706

* 5-in. gauge inside turf wall

gives a comparison of the three gauges over a recent decade. The effect of the turf wall (compare 5T with 5-in.) is small—which may mean that the turf wall is not doing what was expected—and both 5-in. gauges record about 0·1 in. per month less than the 1/1000 acre gauge. The differences look small, but they add up to about 1 in. in an annual total of 28 in., which is about the size (and of the same sign) of currently suspected errors in Meteorological Office pattern gauges. For the present, all rain-gauge readings should be read against the possibility of an error of 2 or 3%, and the large gauge may be the most accurate of any we use. The uncertainty is no more than that in our best estimates of changes in soil water content, and we will be very ready to act on any advice on improved rain-gauging that is the subject of current research elsewhere.

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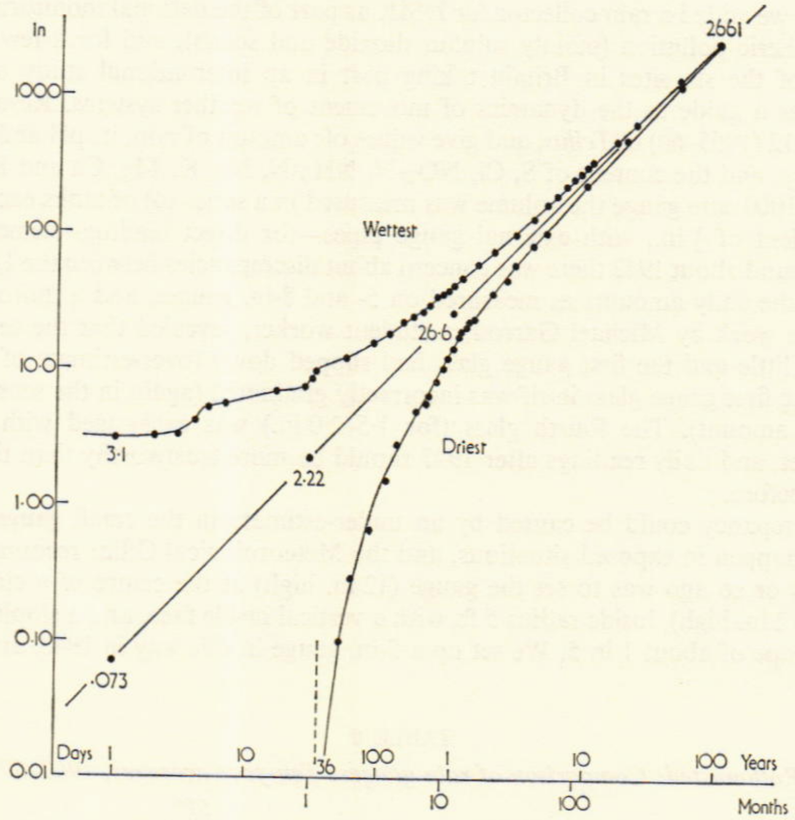

FIG. 13. One hundred years of rain, 1852–1951 (5 in. gauge) on logarithmic scales of amount and time. Points show greatest, or least, total in any chosen length of period. The line of unit slope joins averages.

A hundred years of rainfall. In 1953 a summary of 100 years' of records from the 5-in. gauge was prepared, and has remained on file since. This information will be considered first and then that for 1953–72. Fig. 13 was prepared by going through the records and picking out the maximum fall in one day, two consecutive days and so on up to a total of 100 days: then the unit interval was changed to the month, up to 100 months: thereafter the unit was the calendar year, up to 100 years. Similarly, minimum totals were extracted, starting from the longest period without measurable rain—36 days in 1947. Plotted as log R against log t the curves are remarkably smooth, because there is only a slight seasonal rainfall pattern, and the line of unit slope through the final point gives the sequence of period averages, of which four are marked. Note that at 20 years the wettest and the driest are close to the average, and as a datum for looking at year to year differences a 20-year average should be adequate.

Within a given year almost anything can happen. Table 7 gives the extremes of totals in calendar months, and also the frequency with which a particular month has been the wettest or driest of the year, ignoring the differences in month length. Particularly for the driest, there are sometimes two or three differing only slightly: they have been given half or third weight, and final totals rounded off to the nearest unit.

The individual yearly totals (5-in.) are on Fig. 14. There are obviously periods of wet years (nine in succession, 1875–83 above long-term average) but no long-term secular trend. The distribution of annual totals is on Fig. 15, with a step interval of 2 in. per annum.

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TABLE 7

Rothamsted: Wettest and driest months

(a) 1852–1951: 5-in. gauge

	Total (in.)				Frequency	
	Wettest		Driest		As wettest	As driest
J	5·3	1939	0·32	1855, 1861	8	5
F	4·8	1900	0·04	1891	3	16
M	5·3	1947	*c.* 0·06	1929, 1939	4	13
A	4·2	1920	*c.* 0·12	1912, 1938	0	13
M	4·9	1878, 1889	*c.* 0·46	1896, 1919, 1936	4	6
J	*c.* 6·0	1903, 1936	0·10	1925	6	11
J	6·6	1855	0·13	1921	14	8
A	6·5	1879	0·07	1947	6	3
S	7·7	1896	0·04	1865	8	9
O	6·7	1891	0·04	1947	21	3
N	6·8	1940	*c.* 0·33	1868, 1945	14	6
D	7·5	1914	0·06	1864	12	7

(b) 1952–72: 5-in. gauge

	Wettest		Driest	
J	4·3	1956	0·88	1964
F	3·8	1966	0·04	1959
M	4·0	1963	0·10	1961
A	3·2	1964	*c.* 0·26	1954, 1957
M	4·9	1967	0·56	1956
J	4·5	1958	0·23	1962
J	4·4	1959	0·20	1955
A	5·0	1952, 1956	0·46	1964
S	5·3	1968	0·13	1959
O	*c.* 6·0	1960, 1967	0·22	1969
N	6·1	1970	0·71	1956
D	*c.* 4·5	1959, 1965	*c.* 0·6	1953, 1963

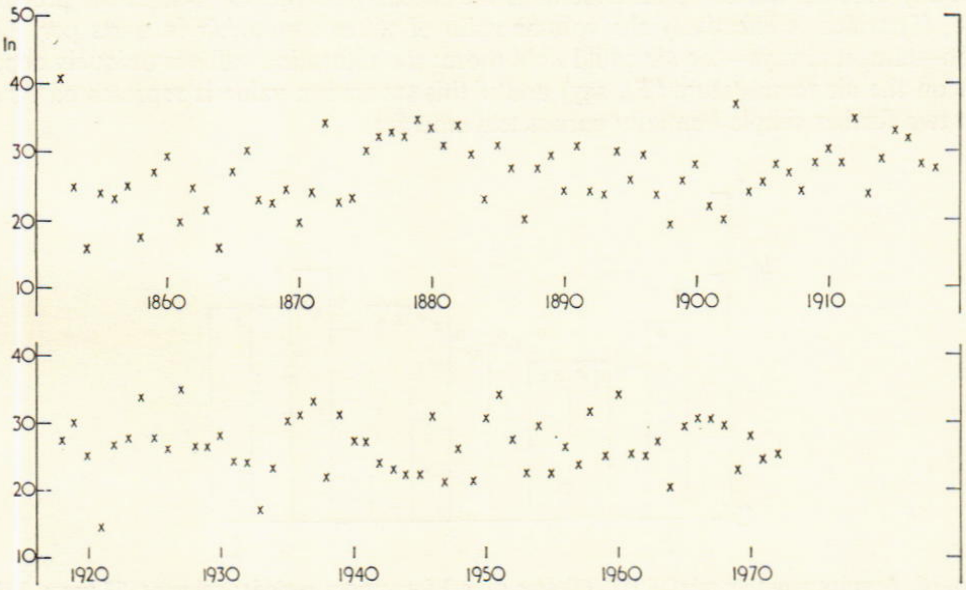

FIG. 14. Annual rainfall, 1851–1972 (5 in. gauge).

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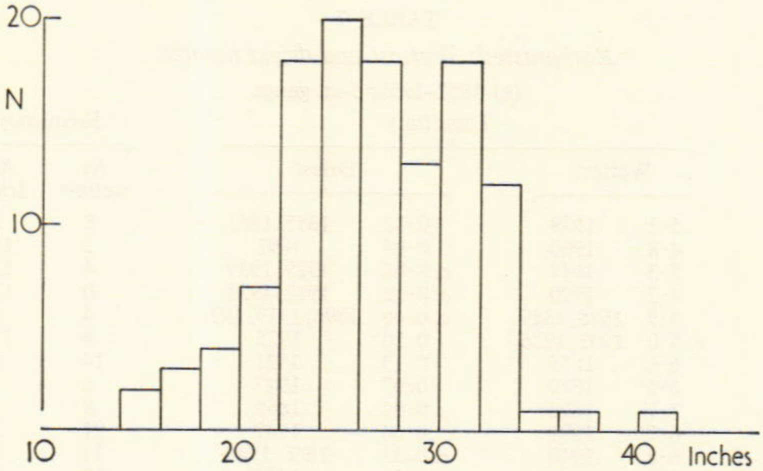

FIG. 15. Frequency distribution of annual rainfall, with step interval 2 in. (As for Fig. 14.)

There is a slight indication of secular change in the seasonal distribution of rainfall (Fig. 16). All three periods agree on a wet mid-winter, a dry spring and a slightly wetter July and August. The main difference is the position of the autumn peak. For the first period, up to 1929, October was the wettest month: during the next 30 years the peak moved into November (not peculiar to Rothamsted) with some possible advantage in early October harvesting: in the third period, 1960–69, the peak has moved to December.

Water in the air

There are many humidity parameters and the choice of the most convenient may not be the same for the study of the movement of wheat rust spores from North Africa as for the study of their germination on Broadbalk. With few exceptions, atmospheric water problems are inseparable from contemporary air temperatures: using symbols for conciseness and clarity the following may help in interpretation of what follows.

At any time the water vapour content of the air can be expressed as a partial pressure, e mb, (1) which is effectively the volume ratio of water vapour/air in parts per 1000. Often—almost always—the air could hold more: the saturation value is uniquely dependent on the air temperature (T_a, say) and if this saturation value is represented by e_a, then two further simple humidity parameters emerge:

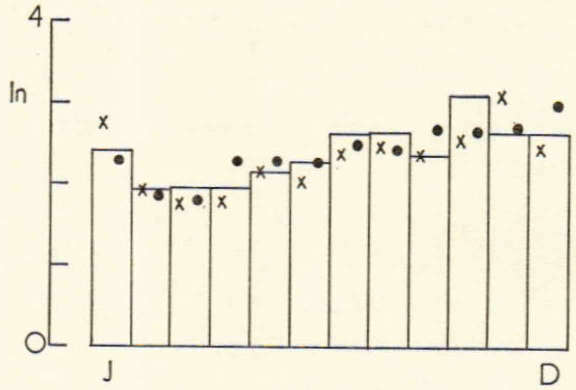

FIG. 16. Average monthly rainfall (1/1000 acre gauge) for various periods: columns, 77 years, 1853–1929; crosses, 30 years, 1930–59; full circles, 10 years, 1960–69.

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(2) Relative humidity; $h = e/e_a$.

Note that this is a fraction, never greater than unity in our problems. For convenience, and often commendably, it is sometimes expressed as a percentage, but there is no need to take it as such into formal equations.

(3) Saturation deficit $= e_a - e$ mb.

The air can be cooled in two important ways. If it is done by evaporating water into it, and all the necessary energy comes from the air, then a limiting temperature is reached, giving another humidity parameter:

(4) Wet-bulb temperature $= T_w$, say.

If the cooling is done without any simultaneous wetting (as over a cold surface) a temperature is reached at which condensation starts: this is the 'dew point' temperature.

(5) Dew point temperature $= T_d$, say.

For both T_w and T_d as for T_a, there are saturation vapour pressures: these can be represented by e_w and e_d, with the identity $e_d \equiv e$.

The parameters are closely linked, the most important formal relationship being

$$(e_d) = e = e_w - \gamma(T_a - T_w), \tag{4}$$

which is the basis of all our field measurements of vapour pressure, e. We record T_a and T_w, the value of the constant γ is known, and because e_w is uniquely dependent on T_w, e can be read off from suitable tables (or calculated by the computer).

Daily changes in vapour pressure. Within a given air mass changes are small, and vapour pressure is one of the very few weather elements of which it can be said that the screen value measured at 0900 hours is within 1 or 2% of the mean for the day. Converted into equivalent dew point temperatures, the value of T_d at 0900 is within a few tenths of 1°C of its mean for the day.

The value, of course, changes with the air mass, i.e. with the weather. Fig. 17 shows the changes, averaged over 4 hours for a period corresponding to the air temperature

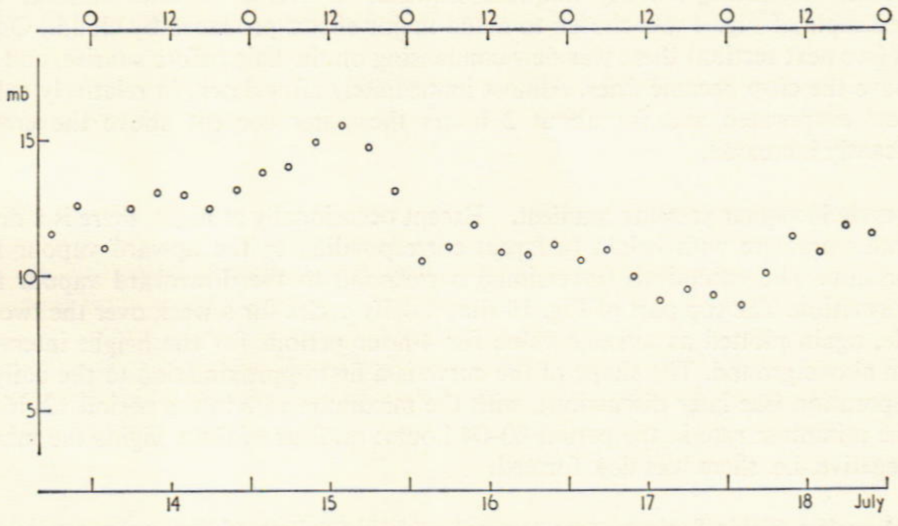

FIG. 17. Changes of vapour pressure at about 2 m above a kale crop, averaged for 4-hour periods. (See Figs 4, 18 and 19.)

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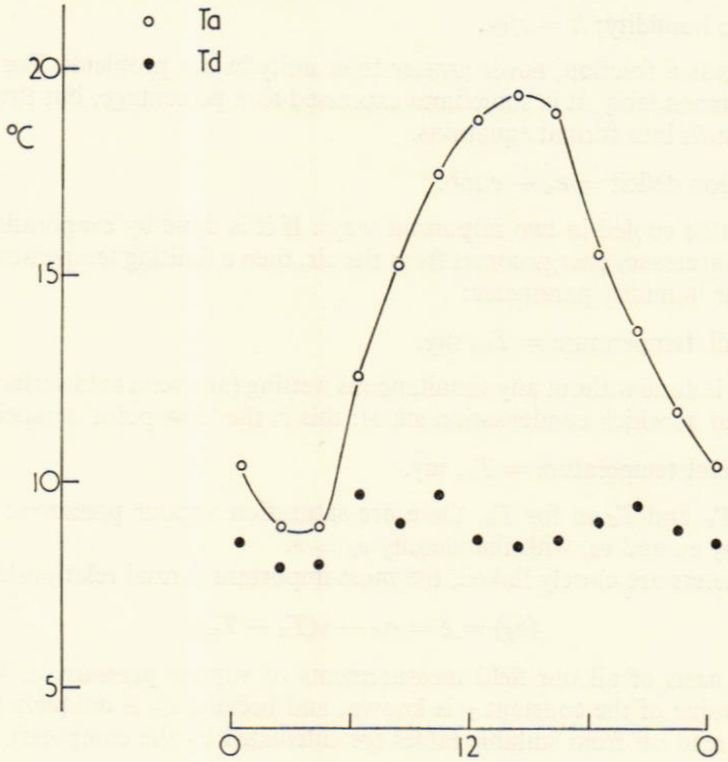

FIG. 18. Average daily cycles of air and dew-point temperature for five fine days, 14–18 July 1971, over kale. (See Figs 4 and 17.)

changes given in Fig. 4. (These are for the S plot over kale.) It is not easy to see a daily cycle in this sequence: the changes are caused mainly by changes in the source of the air brought in by the wind. To eliminate this effect, Fig. 18 gives the five-day average of hourly values of air temperature and dew point temperature, using only alternate hours for the S plot of kale at 270 cm. The daily change in T_d (and hence of e) is small but important, illustrating a fairly frequent sequence of events on clear summer nights. (The example of Fig. 4 was chosen to avoid major effects produced by cloud.) On some nights (see next section) there was dew condensing on the kale before sunrise, and so the air above the crop became drier. Almost immediately after dawn, in relatively calm air, the dew evaporated and for about 2 hours the water content above the crop was significantly increased.

Daily cycle in vapour pressure gradient. Except occasionally at night, there is a decrease in vapour pressure with height (a lapse) corresponding to the upward vapour flux in evaporation. The exceptions (inversions) correspond to the downward vapour flux in dew formation. The top part of Fig. 19 shows daily cycles for a week over the two crops of kale, again plotted as average value for 4-hour periods for the height interval 85–270 cm above ground. The shape of the curve is a first approximation to the daily cycle of evaporation (see later discussion), with the maximum rate in the period 12–16 hours and the minimum rate in the period 00–04 hours: on four of these nights the minimum was negative, i.e. there was dew formed.

Annual cycle. Table 8 gives some average monthly values of dew-point temperatures, measured in the screen over grass: they are derived from the 0900 hour values of dry-bulb

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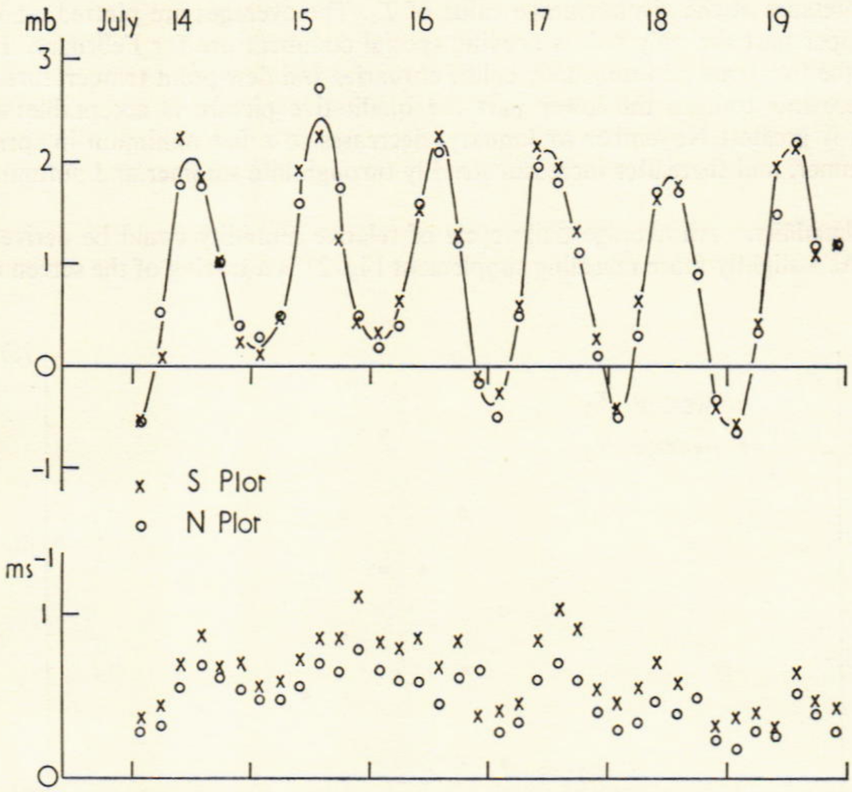

FIG. 19. *Top.* Humidity lapse (85 to 270 cm) over kale for duplicate plots (see Fig. 4) averaged for 4 hour periods.
Bottom. Contemporary wind shear (270 to 120 cm). Crop about 70 cm tall.

and wet-bulb temperatures (T_a and T_w in equation 4). The five-year average is given on the right, with the corresponding vapour pressure and the five-year average of the contemporary mean air temperature (average of daily maxima and minima). Finally, with no assurance that it means very much quantitatively, there is an average relative humidity, calculated from e_d/e_a, where e_d is given in the table, and e_a is the saturation

TABLE 8

Rothamsted: Monthly averages of humidity, 1968–72

	Dew-point temperatures (°C)					Averages			
	1968	1969	1970	1971	1972	T_d °C	e_d mb	T_a °C	h
J	1·1	3·7	2·4	2·3	1·5	2·2	7·2	3·7	0·90
F	−0·3	−2·1	−0·2	1·6	2·4	0·3	6·3	2·4	0·86
M	2·4	1·2	0·2	1·0	3·0	1·6	6·8	4·6	0·80
A	4·1	3·5	3·2	3·4	4·2	3·7	8·0	7·4	0·77
M	6·2	8·8	8·6	6·8	7·0	7·5	10·4	11·2	0·78
J	11·1	9·4	11·3	9·0	8·2	9·8	12·1	13·6	0·78
J	11·3	13·4	11·6	12·7	11·9	12·2	14·1	15·8	0·79
A	12·6	12·3	12·3	12·6	11·5	12·3	14·3	15·6	0·81
S	11·8	11·0	11·2	11·2	8·1	10·7	12·8	13·6	0·82
O	10·7	10·3	8·1	9·3	7·5	9·2	11·6	11·5	0·86
N	4·7	2·9	5·2	3·8	3·5	4·0	8·2	5·8	0·89
D	1·2	1·5	2·3	4·3	3·8	2·6	7·4	3·8	0·92
Year	6·4	6·3	6·3	6·5	6·1	6·3		9·1	

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vapour pressure at the given average value of T_a. The averages are plotted on Fig. 20. In the upper part the only points needing special comment are for February. The first three of the five years had unusually cold Februaries and dew-point temperatures necessarily were low too. In the lower part the qualitative picture is acceptable: relative humidity is greatest November to January, decreases to a flat minimum in spring and early summer, and thereafter increases steadily through late summer and autumn.

Relative humidity. An average daily cycle of relative humidity could be derived from Fig. 18. As a slightly more revealing supplement Fig. 21 is a tracing of the screen records

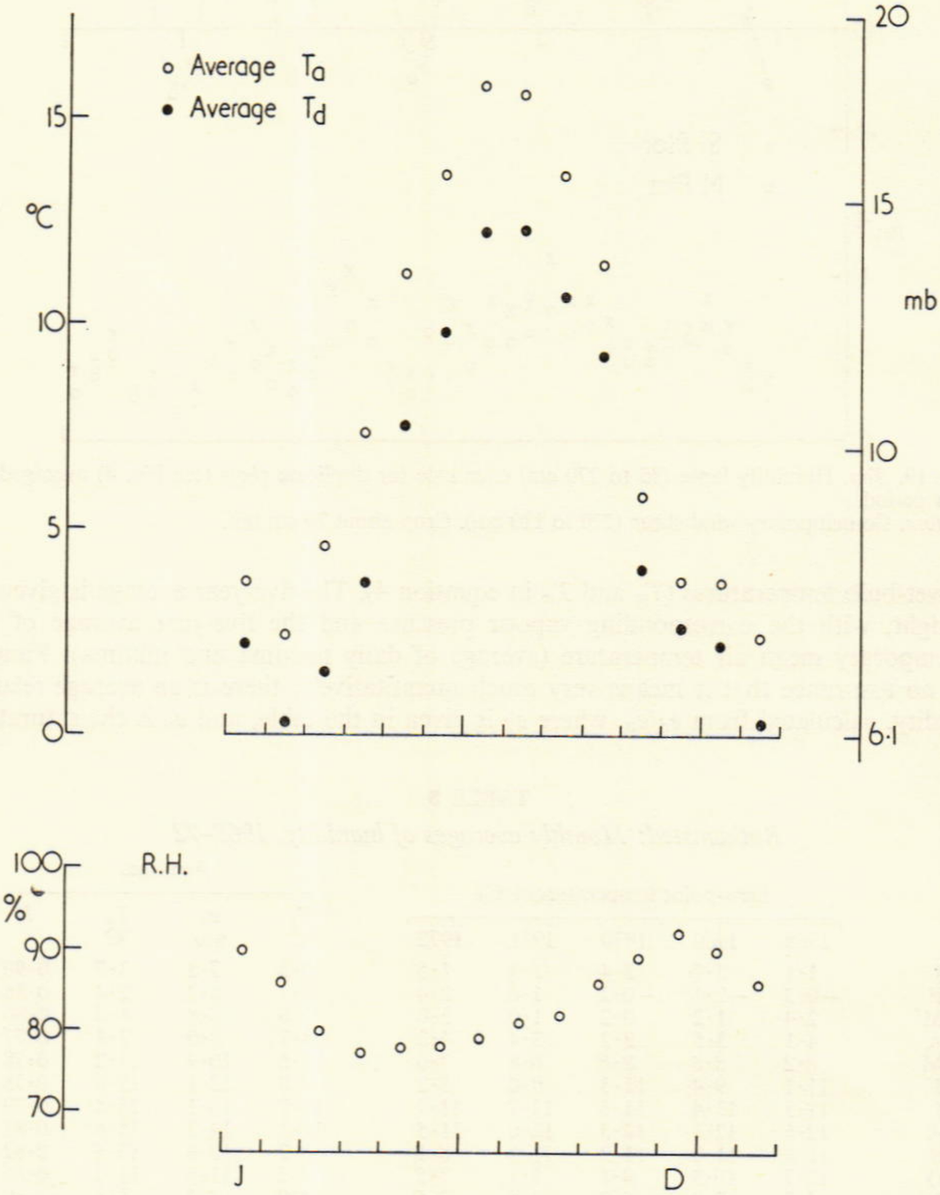

FIG. 20. Annual cycles of average monthly air temperature, dew point temperature and relative humidity (five years, 1968–72). On the right, above, is a scale of vapour pressure corresponding to the dew-point temperatures.

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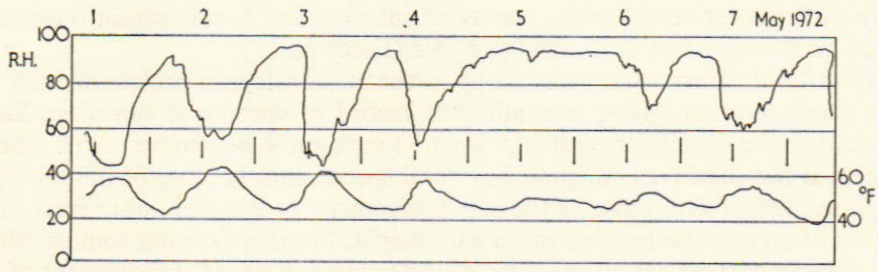

FIG. 21. Relative humidity (%: above) and temperature (°F: below) for a week, 1–8 May 1972. The tracing has been adjusted to give correct relative timing. Note that the recording pens move in arcs and the curvature is obvious in the humidity trace for 3 May.

for a week, taken from an instrument that records both air temperature (here in °F, scale on the right) and relative humidity, using stretched hair as the sensor. At its best the hair hygrometer is probably correct to within 2%, but the zero tends to shift, and it *may be* that the maximum recorded during the week should have been 100% rather than the 97% shown on 3 May. Because of the near constancy of the vapour pressure (Fig. 18), the behaviour of the ratio $h = e/e_a$ is dictated by the changes in e_a, i.e. of T_a, the air temperature. Hence the daily cycle of relative humidity is almost exactly out of phase with the air temperature.

Relative humidity should be avoided as a humidity parameter wherever possible, but it cannot be ignored in some important contexts. It is the relative humidity of the ambient air that determines the equilibrium water content of porous systems—including hay and grain, soil and some of the soil fauna.

Wind

Moving air is retarded by friction, and the landscape is a rougher surface than a seascape. Hence surface wind speeds decrease with distance from the coast, and it happens that because of our geographical position and the relative frequency of westerly and easterly winds, Rothamsted is close to being the calmest part of Britain in the long-term annual averages of surface wind speeds. In common with nearly all climatological stations our early wind records are simply a note of wind direction and of a 'Beaufort Force' (on a scale 0–12), usually at only one time a day. For experiment we started using a cup anemometer at 2 m above ground in 1944 and, with the counter read at 0900 hours daily, the run-of-the-wind has been recorded, in miles per day, since then. Table 9 shows

TABLE 9

Rothamsted: Average monthly wind speed at 2 m above grass (km day^{-1}), 1968–72

	Average	Range
J	222	200–250
F	245	200–310
M	270	235–330
A	263	200–305
M	210	185–265
J	197	175–225
J	161	135–195
A	175	150–230
S	167	125–210
O	192	160–235
N	237	215–275
D	216	190–240
Year	213	200–225

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monthly averages for recent years, converted into km day^{-1}, and within these averages there can be periods of calm (Force 0) or gale (Force 8).

In 1954 a Dines anemometer was set up in the meteorological enclosure, with sensors at 10 m above ground, giving a continuous record of speed and direction. Since the record started the maximum gust has been 73 mph on 4 November 1957. The Dines instrument is not sensitive enough at low wind speeds and, because of this, comparison of integrated values with those of the cup anemometer at 2 m does not reveal universal experience of an increase in wind speed with height. In many farming contexts this wind shear is very important. (It affects rates of water use and growth; movement of spores, pollen, insects; possibly the risk of lodging.) Accordingly, the research instrumentation always includes a vertical array of small sensitive cup anemometers suitably spaced from just above the crop to about 2 m clear of it. One item of detail may suffice here, as informative and a little disturbing. The lower part of Fig. 19 shows the values of the wind speed difference between 270 and 120 cm above ground, over the two kale crops (then about 70 cm tall) for the same 4-hour periods as for the vapour pressure lapse. The differences between the two sites, about 100 m apart, are large, and consistent over a period of six weeks so far studied. There is no suspicion of instrumental error and the cause is probably some funnelling of air movement by the belt of tall trees close to the south edge of the *S* plot.

The general pattern, true of the absolute wind speeds too, is that the daily cycle of wind speed is rather like that of air temperature and of humidity lapse, building up from a minimum about dawn to a maximum after noon, and declining thereafter to and beyond sunset.

Evaporation

In some contexts 'evaporation', 'transpiration', and 'water use' are synonymous, but the first is the more generally useful in agricultural physics. For water balance studies it is convenient to use rainfall units and express an evaporation rate as depth per unit time (e.g. mm day^{-1}), but for energy balances it is often more desirable to use an energy unit.

The vapour flux from natural surfaces is dominantly upward, but at some times of the year there may be night-time periods when it is downward—usually when the net radiation is negative. Then there is a gain of water in the plant/soil system as 'dew', but the amounts are small and not easy to measure. Monteith estimated that the maximum possible annual gain for us is only 4 or 5 mm. Occasions of 'heavy dew', very obvious and frequent in spring, early summer and autumn, occur because of distillation of water from relatively warm wet soil under the crop, and may be accompanied by guttation (Plate 1). This is not a gain in the plant/soil system but is the beginning of a slightly accelerated evaporation in the first few hours of the succeeding day. Monteith (1957) measured some nightly rates of up to 0·02 mm h^{-1} equivalent depth on short grass.

Measurement for cropped soil is not easy, and we have used calculated values, since 1948, for design and interpretation of irrigation experiments, and as the basis for technical advice on relevant irrigation and hydrological problems. (See 'Potential Evaporation' later.) Most meteorological services have some form of open water pan evaporimeter, but designs vary greatly from country to country, and all are subject to sources of error and uncertainty, of which only two will be made explicit. The evaporation over a given period is the sum of the fall in level of the water and the amount of rain in the period, so that any uncertainty in measured rain is carried into the estimate of evaporation. Winter estimates are uncertain when the water freezes, and occasionally this uncertainty is increased when snow falls on the frozen surface.

We installed the standard British Meteorological Office evaporation tank in 1947. This, designed by Symons about 1870, is of galvanised iron, 6 ft square, 2 ft deep, and

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PLATE 1. Dew and guttation on grass. A small part of this water may have condensed out of the atmosphere, but nearly all has come from the soil, either directly (small drops) or through the plants (large drops). (From I. F. Long.)

[*facing page 196*

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set in the ground so that a 3-in. rim projects, and the water level is kept at about ground level by measured additions or abstractions as necessary. The level is read daily, by hook gauge, to the nearest 0·01 in.

Potential evaporation (Potential transpiration). Two years of measurements, and of theoretical analysis of the results, produced a relation between the rate of evaporation from short turf, never short of water, and the prevailing weather, based primarily on consideration of energy balance. Where the necessary components can be measured they go into the formal equation, but in the widespread use of it since 1948 this condition has been rarely satisfied, and most calculations have been based on empirical relations (e.g. equation (2)), leading to an expression for potential evaporation rate in terms of four standard meteorological elements: duration of bright sunshine, air temperature, water vapour pressure in the air, and average wind speed. For the taller farm crops the estimate is expected to be a slight under-estimate of rate of water use while there is a complete (or nearly so) crop cover of fresh green vegetation, not short of water (French, Long & Penman, 1973).

Because of the presence of empirical relationships in the format the estimates are biased somewhat toward average values, and year to year estimates at a given time of the year tend to be conservative, more so than measured values of open water evaporation.

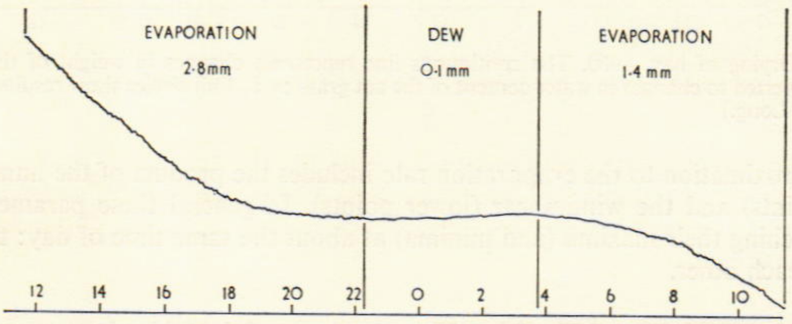

FIG. 22. Tracing of a record of changes in weight of a block of soil carrying grass, during 24 hours of clear weather before cutting for hay, 28–29 May 1960. (From J. L. Monteith.)

Daily cycle (Fig. 22). For several years a transpiration gauge was used in the crop alongside the meteorological enclosure. This gauge was a metal box 56 × 56 in., 25 in. deep, filled with soil and carried on a suspension system, which, with suitable intermediate parts, was connected to a pen that recorded changes in weight on a rotating drum chart. Fig. 22 is a copy of an untypical record, chosen to display the basic character of the diurnal cycle in rate of water use, free from the fluctuations produced by intermittent cloud, or showers. The rate is almost constant for 3 or 4 hours after noon, gradually decreases thereafter to about sunset (2000 hours at the end of May), then becomes slightly negative until about sunrise (near 0400 hours), then slowly increases until about 0800 hours and thereafter becomes much more rapid. The grass around (and on) the gauge was then cut for hay, and over the haymaking period samples from the field were taken and dried to give an estimate of water content. The cut grass on the gauge was turned at the same times as the field hay. Fig. 23 shows the gauge record of drying as a continuous line, and the sampling results as full points, and including some night-time values. The fit is impressive. Note that the drying grass can behave as a porous absorbent and can take up water in addition to the superficial collection of dew.

An alternative assessment of the daily cycle can start from Fig. 19. There are important corrections needed for the degree of atmospheric stability, but, before they are made,

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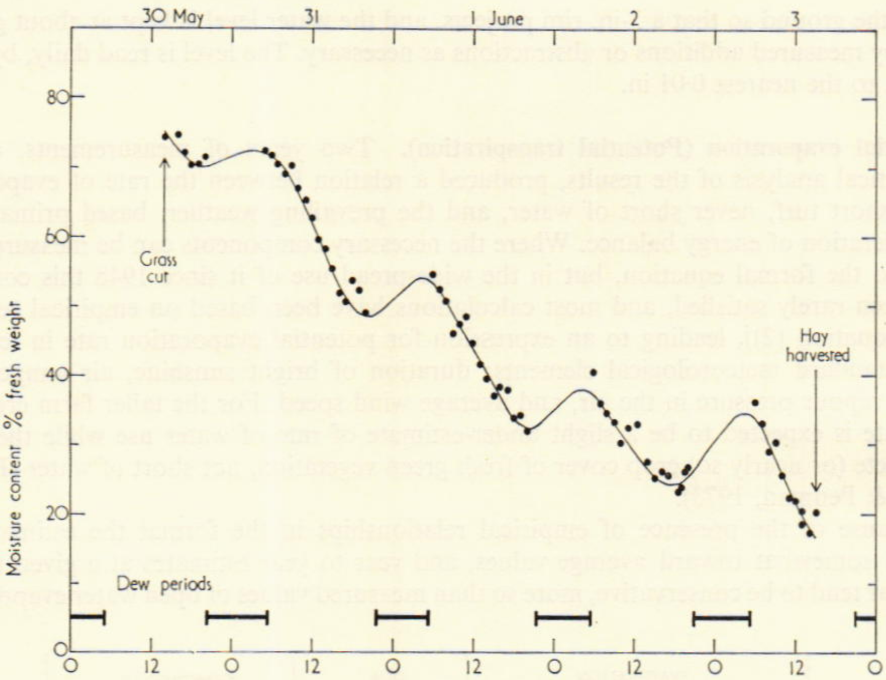

FIG. 23. Drying of hay, 1960. The continuous line represents changes in weight of the gauge (see Fig. 22) converted to changes in water content of the cut grass on it. Full circles show results of sampling. (From I. F. Long.)

a first approximation to the evaporation rate includes the product of the humidity lapse (upper points) and the wind shear (lower points). In general these parameters are in phase, reaching their maxima (and minima) at about the same time of day: their effects reinforce each other.

Annual cycles (Table 10 and Fig. 24). The upper part of the table gives average monthly values of measured evaporation from the Symons tank, first for the whole period of

TABLE 10

Rothamsted: Evaporation

(a) Open water (E_O, Symons Tank) (mm per month)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
1948–72 (25)	4·5	8·5	30·5	53	79	92	92	76	56	31·5	13·5	5·5	542
1960–69 (10)	4·5	7·5	32	51	77	93	88	76	56	31	14·5	4	534
Most (1949)	7·5	15	32	64	82	96	142	107	68	33	10·5	10·5	668
Least (1954)	7	3·5	23	57	62	70	72	53	51	25	13·5	10·5	447

(b) Potential evaporation, E_T and E_O

	J	F	M	A	M	J	J	A	S	O	N	D	Year
1968–72 (5) E_T	2·5	8	30	51	74	85	83	64	44	19	4·5	−0·5	465
E_O	5	6·5	28	52	76	93	96	78	64	36	16	6	554

records and then for the ten years (1960–69) that are picked out in earlier sections. To give some idea of variability, totals for extreme years are added. For potential evaporation, only five years of estimates are used, and with them are the corresponding open water averages, which do not differ much from the 25-year values.

The figure (left) shows the seasonal trend in the open water evaporation, E_O (25-year averages) plotted without points. Two sets of discrete points show the five-year averages

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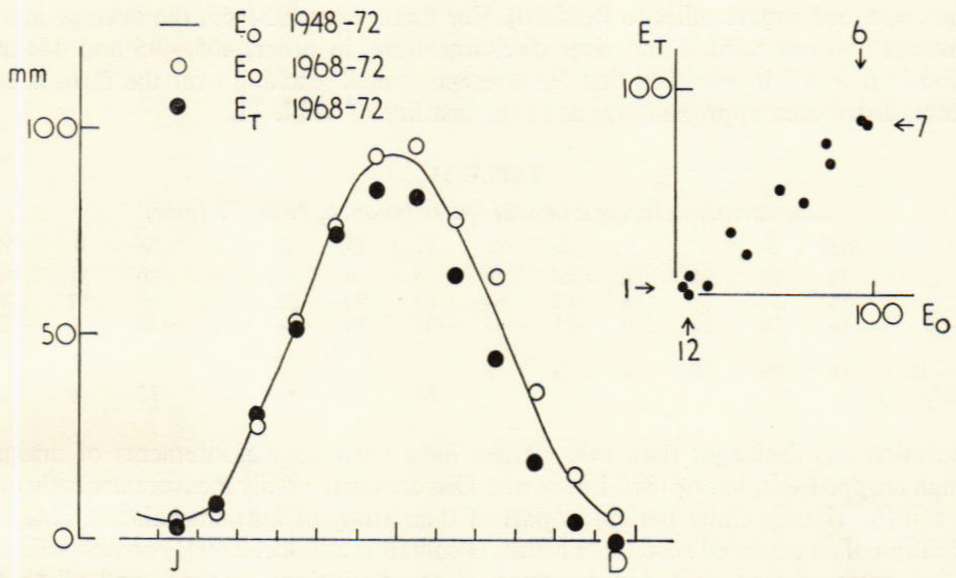

FIG. 24. Annual cycle of evaporation. *Left*. The line is the measured 25 year average for an open water surface (Symons tank) and the open circles give the five year average, 1968–72. Full circles show the calculated potential evaporation for the same five years. *Right*. The phase relationship between the two five year sets of averages. The time sequence is clockwise, January to December.

for E_O and for E_T, and the expected strong correlation is obvious. The departure from perfection is not random but is a phase effect revealed in the small scale inset where contemporary averages are plotted against each other month by month. The points fall on a very smooth ellipse with potential evaporation leading open water evaporation by about a week in phase. This is an effect of heat storage in the tank: from January to July the water is getting warmer, using some of the solar radiation income that would otherwise be used in evaporation; from July to January the water is getting cooler, contributing to the energy used in evaporation. A similar switch from storage to release occurs in soils under crops, and though it can be taken into account in complete energy balances it is rarely important in plant growth problems.

The negative value of the potential evaporation in December is questionable. From November to January the formal equations have to take in very small differences between quite large quantities and within the random scatter that this produces there is evidence that there is also a biased error leading to an underestimate of the potential evaporation. The uncertainty in these three months is no more than that in the estimates of the monthly rainfall.

Average water balance. As a bridge to the next section, Table 11 gives an idealised balance sheet for a year in which the farm gets average rainfall every month, well distributed in time, the rest of the weather is average so that the potential evaporation is average, and all the farm is under short grass. For a reason that will be obvious after a little study, the year starts on 1 May. Until 31 August evaporation exceeds rainfall, and the soil gets drier—to an accumulated deficit of 74 mm then. During September and October the soil is re-wetted without excess, and it is in November that all the profile is re-wetted and there is a first surplus for drainage. This condition is maintained to the end of April.

'Idealised' does not mean absurd. We are on the edge of the Thames catchment (3810 square miles), close to the headwaters of the Lee (400 square miles) and just south

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of the Ouse (565 square miles to Bedford). For these, over 1954–65, the average annual differences between rainfall and river discharge were, in order, 465, 495 and 444 mm. Obviously it is a fair inference that the average annual leaching over the farm is near 240 mm, distributed approximately as in the last line of Table 11.

TABLE 11

Rothamsted: Average annual water balance, 1968–72 (mm)

	May	J	J	A	S	O	N	D	J	F	M	A	Year
E_T	74	85	83	64	44	19	5	0	2	8	30	51	465
R	56	57	61	58	65	64	67	74	56	46	45	57	706
$E_T - R$	18	28	22	6	−21	−45	−62	−74	−54	−38	−15	−6	−241
$\Sigma(E_T - R)$	18	46	68	74	53	8							
Drainage (d)							54	74	54	38	15	6	241

Evaporation and drainage: Bare soil. There have been no measurements of drainage through cropped soil, but in 1870 Lawes and Gilbert started daily measurements through bare soil (previously under barley) as part of their study of nutrient balance. Since the publication of an extended account of results (Penman & Schofield, 1941) no new information has emerged that calls for re-appraisal of conclusions reached, and all that is needed here is to bring some of the evidence up to date.

Alongside the 1/1000-acre raingauge three blocks of soil of the same area were isolated, underpinned and bricked-in to form a box, presumed water-tight. Any drainage water was collected and a sample chemically analysed. Of the three, the shallowest (20 in. deep) seemed, in 1941, to be free from any leak, the deepest (60 in.) was very slightly suspect, but the intermediate gauge (40 in.) certainly had an inward leak, giving clearly greater totals of apparent drainage than either of the other two. These rarely differed much, and always in the direction to be expected because of the difference in depth and the absence of any suction at the lower surface where the percolating water emerges before dripping into the collecting funnel below. During the 100 years, the soil has been undisturbed except in pulling out seedling weeds and lifting off moss: it has packed down very firmly, and in many respects it is not representative of bare soil elsewhere on the farm during periods between crops. Evidence here is limited to results from the 20-in. gauge.

TABLE 12

Rothamsted: Average response of 20-in. draingauge (mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
1871–1939 (69)													
$R - d$	11	14	23	35	40	43	50	48	40	34	17	11	365
1940–59 (20)													
$R - d$	16	11	22	28	43	40	47	48	39	31	16	11	350
1960–69 (10)													
R	59	47	46	58	59	58	64	62	68	67	69	76	730
d	53	33	31	20	17	17	17	15	29	40	50	59	380
$R - d$	6	14	15	38	42	41	47	47	39	27	19	17	350
Eo	4	8	32	51	77	93	88	76	56	31	14	4	535

Table 12 gives average annual cycles of values of R and d, in the first two lines simply as their difference for the period 1871–1939 (effectively that covered by the 1941 survey), and for the next 20 years to 1959. For the decade 1960–69 the components are given, plus the corresponding values of open water evaporation from the Symons tank (E_O). For the year, it is safe to set $E_B = R - d$, but great caution is needed in making decisions about the validity of the equation in summer months: the values given are correct in scale, but, in addition to carry-over effects, results are dominated by a simple principle.

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Drying of bare soil is essentially a skin effect and the amount is determined by the length of time that the surface is wet. From about October to February this is effectively all the time, and the bare soil behaves much the same as an open water surface, but in summer the surface dries in a few days after rain and evaporation rates then decrease very rapidly. So summer totals are largely determined by frequency of re-wetting by rain, and hence are strongly correlated with total summer rain, whereas the winter totals are not detectably dependent on total winter rain. The summer effect is carried through into the annual totals. Plotting annual values of $R - d\,(=E_B)$ against R for the period 1938–72 produces a distribution which, visually, belongs to the same population as those for 1881 to 1937 (Penman & Schofield, 1941, Fig. 6): there is a little more confusion but no new information. However, for good reasons, the 1941 survey ignored the results in the first ten years, 1871 to 1880, and looking at these afresh the first eight, to 1878, seem to lie significantly outside the general distribution of the other 94 points in the sense of showing greater values of E_B. The effect might be an indication of how long it took the previously cultivated and cropped soil to settle down and (or) to get it free from weeds.

Acknowledgements

Some of the preceding material has come out of research projects and some out of the routine recording. As a gesture of thanks for the first I have occasionally given an acknowledgement of source in the caption to a figure. For the second, without major injustice, I can restrict my thanks to two colleagues, past and present, and thereby get back to 1911 when Will Game joined the department as a boy. On his retirement in 1962 he was succeeded as senior observer by Arthur Day, who had joined him as assistant observer in 1957. During this valuable long period of continuity there has been sustained interest, keenness, and great competence, and I am very grateful to both men.

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