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Calculation of evapotranspiration from potatoes

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Summary

Data from sprinkling experiments with potatoes were used to calculate the actual and potential evapotranspiration from the crop during the growing season, using standard meteorologic data. During the experiments the moisture extraction from the effective root-zone was determined by soil sampling to get the time of sprinkling for the fields with different moisture treatments.
The water use by the crop for the different periods was also derived from the water balance and both values were in good agreement in periods without extreme conditions of precipitation. This showed that the derived relations between crop height and surface roughness, between soil cover, light intensity, crop characteristics, soil characteristics and diffusion resistance, and between maturation and internal plant resistance were reasonably established.

Introduction

Evapotranspiration from cropped surfaces is governed not only by the meteorological conditions, but also by factors related to the crop itself and to the soil physical conditions. For irrigation practice, as well as in many hydrological investigations, it is very important to determine the actual as well as the potential water use of a crop from meteorological data. Particularly for arable crops the practical application is still partly a matter of speculation, since a number of aspects are still more or less unknown.
For several years sprinkling irrigation experiments with potatoes were performed at the experimental farm of the Institute. The purpose of these experiments was not primarily transpiration research but to obtain information on the increase in yield caused by sprinkling. The available data of soil moisture conditions and crop development were given in internal reports of the Institute.
Recent developments in transpiration research made it valuable to use the data from these sprinkling experiments in a study of the influences of crop development and moisture conditions on water use by potatoes.

Available data

Soil type and soil moisture data
The experiments were performed on a coarse sandy soil with 6 % humus in the top 30 cm, and 2.5 to 3.0 % in the layer of 30 to 60 cm. The available soil moisture in the top layer of 1 m was 100 mm. About 72 mm is available from the humous top

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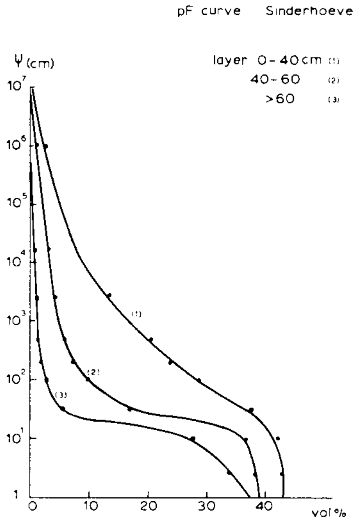

Fig. 1 Soil moisture characteristics.
1: 0–40 cm layer; 2: 40–60 cm layer; 3: 60 cm

layer of 40 cm. The coarse sand with gravel in the layers below 60 cm do not contribute much to the total amount of available water. The soil moisture characteristics of the different layers are given in Fig. 1. The effective root-zone of the potato crop is in fact restricted to the humous top layer of 40 cm.

During the sprinkling experiments the moisture content in the different layers was determined periodically by soil sampling. In most cases the soil samples were taken from the layers 0 to 20 cm, 20 to 40 cm and 40 to 60 cm. In a few cases also data from the 60 to 80 cm layer were present, but these data did hardly show any variation in moisture content with time. For this reason the change in water content of the profile was usually calculated for the top 60 cm.

Most of the data for 1964 concern only the top 20 cm. In order to obtain information concerning the mean moisture content in the effective root-zone of the crop and

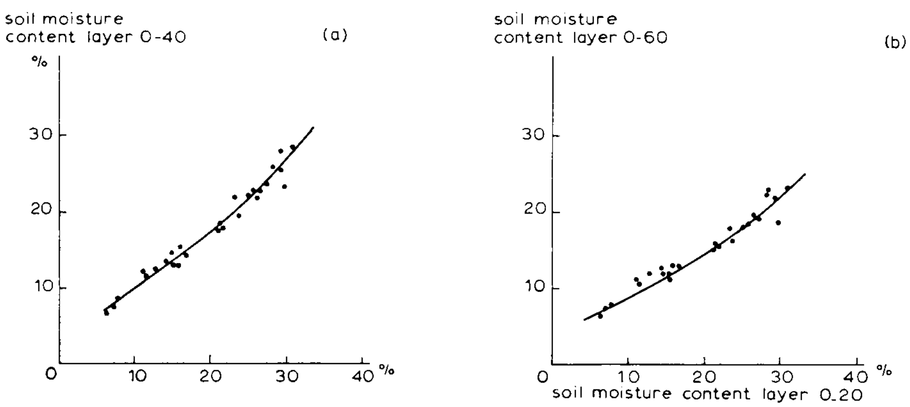

Fig. 2 Relation between the soil moisture content of the top 20 cm and the mean moisture content of the top 40 cm (a) and the top 60 cm (b)

to obtain data on soil moisture changes in the profile, the relations shown in Fig. 2 were used to derive the requiured data from the top 20 cm.
The absence of soil moisture data from the deeper layers will give an overestimate of evapotranspiration when using the water-balance equation under wet conditions and a discharge to these deeper layers is present.

Irrigation frequency
The time of sprinkling was based on the moisture extraction from the top layer of 40 cm. Generally the following moisture treatments were present: a. irrigation after 25 % extraction of the available moisture; b. after 50 %; c. after 75 % and d. no irrigation. The various moisture treatments will be indicated as v_3, v_2, v_1 and v_0, respectively. In 1962, 1965 and 1966 the weather conditions were such that only the v_3 field received additional water by sprinkling irrigation. Table 1 gives the moisture treatments.

Table 1 The soil moisture treatments during the years of the experiments

Year	Irrigation after a moisture extraction of			No irrigation
	25 %	50 %	75 %	
1959	v_3	—	v_1	v_0
1961	v_3	v_2	v_1	v_0 [1]
1962	v_3	—	—	v_0
1963	—	v_2	—	v_0
1964	v_3	v_2	v_1	v_0
1965	v_3	—	—	v_0
1966	v_3	—	—	v_0

[1] An irrigation gift after flowering

Crop development
Each year the date of planting, the date at which the crop came up and of harvesting were noted. Particularly during the first four years not too much attention was given

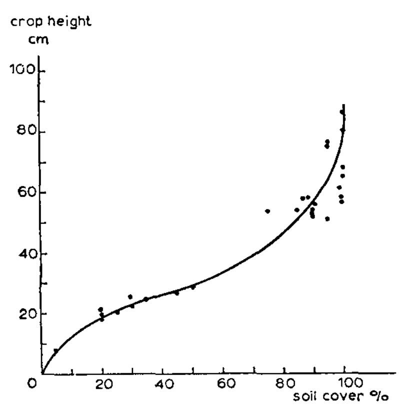

Fig. 3 Relation between crop height and percentage of soil cover for a potato crop

to the collection of data concerning crop height and soil cover. During these years only two or three data of soil cover or crop height during growth were collected. More attention to crop development was given in the last three years, during which both data were collected periodically. The relation between height and soil cover of the potato crop derived from these data is presented in Fig. 3. This relation is useful to get additional information concerning crop height or soil cover during the first four years.

The percentage of dead leaves was used as a measure of the maturity of the crop during growth.

Meteorological data

The meteorological data required for the calculation of evapotranspiration, such as duration of bright sunshine, temperature, humidity, wind velocity and precipitation, were measured daily at the meteorological observation field of the experimental farm of the Institute.

Calculation of evapotranspiration

Actual evapotranspiration can be calculated for practical purposes with a combined aerodynamic and energy balance approach (Rijtema, 1965), taking into account the properties of the crop and the soil. The general equation is:

$$E_{re} = E_T^{re} + E_I = \frac{\triangle H_{nt}/L + \gamma\{E_a' + f(z_o, d)\, u\, R_c E_I\}}{\triangle + \gamma\{1 + f(z_o, d) u\, R_c\}} \quad (1)$$

where E_{re} is the real evapotranspiration, E_T^{re} the real transpiration from the crop, E_I the evaporation of the precipitation intercepted by the crop, $\triangle$ the slope of the temperature-saturated vapour pressure curve, H_{nt} the net radiation, L the latent heat of vaporization, γ the psychrometer constant, $E_a' = f(z_o, d)\, u\, (\varepsilon_a - e_a)$, ε_a the saturated vapour pressure at air temperature, e_a the actual vapour pressure, $f(z_o, d)$ a function depending on the roughness length (z_o) and the zero plane displacement (d) of the evaporating surface, u the wind velocity measured at 2 m height and R_c the diffusion resistance of the crop.

When it is assumed that R_c equals zero, the maximum possible evaporation (E_{wet}) from the surface under consideration can be calculated. Eq. 1 transforms in that case into:

$$E_{wet} = \frac{\triangle H_{nt}/L + \gamma E'_a}{\triangle + \gamma} \quad (2)$$

It is difficult to determine exactly the evaporation term E_I, particularly in periods with much precipitation, when the crop does not become dry between the successive showers. The calculated amount of interception is too high in that case. Since the calculated evaporation (E_{wet}) of a wet crop surface with the same properties as the crop considered gives the maximum value, the value of E_I may not exceed E_{wet}.

Based on this argument, Rijtema (1968) combined Eq. 1 and 2, which resulted in the expression

$$E_{re} = E_T^{re} + E_I = \frac{\Delta + \gamma}{\Delta + \gamma\{1 + f(z_o, d)u\, R_c\}}(E_{wet} - E_I) + E_I \qquad (3)$$

Data derived from literature

No data of the relation between precipitation and the amount intercepted by a potato crop were available. However, an error in the value of E_I is not disastrous, as the term E_I operates in Eq. 3 as a correction factor, of which the effect on E_{re} strongly depends on the value of the ratio $(\Delta + \gamma)\ [\Delta + \gamma\{1 + f(z_o, d)\ u\ R_c\}]^{-1}$. For this reason the interception data of tall grass given by Rijtema (1965) were used.

The value of $f(z_o, d)$ depends on crop height and on wind velocity. The combined effect has been expressed for a grass crop by Rijtema (1965) as:

$$f(z_o, d) = g(l) \cdot h(u) \qquad (4)$$

where $g(l)$ is a function of crop height with the same dimensions as $f(z_o, d)$, and $h(u)$ is a dimensionless factor which depends on wind velocity. Calculations of Szeicz et al. (1969) for a potato crop resulted in similar values for $g(l)$ and $h(u)$ as those given by Rijtema for a grass cover. Values of $g(l)$ and $h(u)$ used in the present paper are given in Table 2 in relation to crop height and wind velocity, respectively.

The diffusion resistance R_c takes into account the geometry of the evaporating surface, as soil cover and leaf area, the stomatal opening under influence of light intensity and the transport resistances in the liquid flow path. Rijtema (1968) assumed that the combined effect of these factors can be given with the expression

$$R_c = R_c^l + R_c^c + R_c^{\psi} \qquad (5)$$

where R_c^l is the diffusion resistance term depending on light intensity, R_c^c the factor depending on soil cover and R_c^{ψ} the factor giving the effect of soil moisture conditions on the value of R_c.

Rijtema (1965) used the mean radiation intensity during the balance period as a measure for the light-dependent factor, controlling stomatal opening under field conditions. The relation between R_c^l and mean radiation intensity during the day-time hours is given in Table 3.

Table 2 Values of g(l) in relation to crop height and values of h(u) in relation to wind velocity at 2 m height

Crop height (cm)	0	2	5	10	20	30	40	50	70	90
$g(l)$	0.18	0.23	0.47	0.74	1.00	1.12	1.22	1.32	1.42	1.50
Wind velocity (m . sec-1)	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	7.0
$h(u)$	1.32	1.17	1.05	0.96	0.90	0.86	0.79	0.75	0.72	0.69

Table 3 Values of the diffusion resistance R_c^l and mean radiation intensity during the day-time hours

Radiation intensity (cal. cm-2 . min-1)	0.10	0.15	0.20	0.25	0.30	0.38	$>$ 0.38
R_c^l (mm Hg . day . mm-1)	3.77	2.76	1.94	1.21	0.66	0.0	0.0

Table 4 Values of the diffusion resistance R_c^c and soil cover

Soil cover (%)	10	20	30	40	50	60	70	80	90	100
R_c^c(mm Hg . day . mm-1)	2.33	1.72	1.27	0.90	0.60	0.35	0.18	0.08	0	0

Rijtema and Ryhiner (1968) give some data of R_c^c in relation to soil cover for spring wheat. Calculations of Feddes (1968) of values of R_c^c in relation to soil covei for spinach and red cabbage resulted in similar values as those given by Rijtema and Ryhiner. The scatter in the data is rather large which is mainly caused by the distribution of the precipitation during the experiments, which effects the evaporation from the bare soil. The data used in the present study are given in Table 4.

Reconstruction of crop development data

The relation between crop height, soil cover and point of time within the growing season is more or less fixed for crops harvested once a year. Between the different years a shift in time can be present, depending on the starting point of growth in spring time.

The scantily available data and those derived from Fig. 3 were plotted versus time. A curve was drawn through these points. An example of the procedure used for the data of the v_3 and v_0 fields in 1961 is given in Fig. 4. From these curves the mean crop height and mean soil cover for each balance period could be estimated.

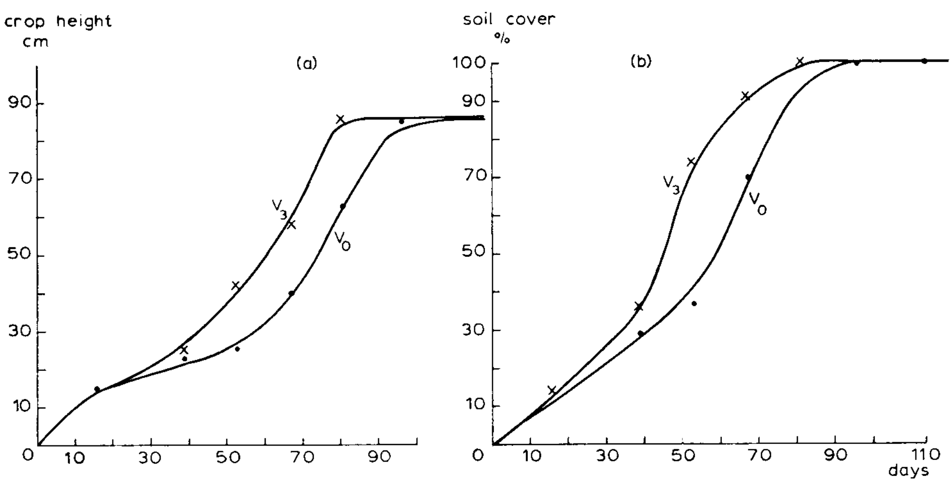

Fig. 4 The relation between crop development and time in 1961 for an unirrigated potato field (v_0) and a frequently irrigated one (v_3). a: change in crop height with time; b: change in soil cover percentage with time

Soil moisture conditions

The effect of climate and soil moisture conditions on the reduction in transpiration was calculated from the relation between the diffusion resistance R_c^{ψ} and the poten-

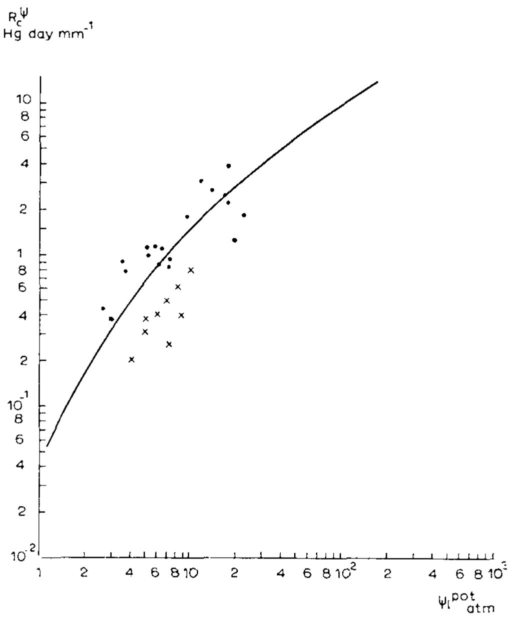

Fig. 5 Relation between the crop resistance R_c^{ψ} and the potential suction ψ_l^{pot} in the leaves. Part of the data was derived by Ryhiner (1969). The other data were derived from the experimental data in 1959: x: with irrigation; •: without irrigation

tial suction ψ_l^{pot} in the leaves. According to Rijtema (1965) this relation can be given by the expression

$$R_c^{\psi} = f(\psi_l^{pot}) = f\left\{E_T^{pot}(R_{pl} + {}^b/_k) + \psi\right\} \tag{6}$$

where E_T^{pot} is the potential transpiration rate, calculated with Eq. 3, assuming R_c^{ψ} equals zero but taking into account the values of R_c^{l} and R_c^{c} ; R_{pl} the transport resistance for liquid flow in the plant, b a geometry factor of the root system depending on rooting depth, root intensity and root activity, k the capillary conductivity at mean suction ψ in the effective root-zone of the crop.

It appears from data given by Ryhiner (1969) from experiments with potatoes in 1967 and from calculations performed with the 1959 data that for a full grown potato crop the value of R_{pl} equals 1 atm. day . mm^{-1} and the value of b 3.10^{-4} atm. The relation between R_c^{ψ} and ψ_l^{pot} calculated from these data is given in Fig. 5. The data derived from the irrigated fields show a tendency to give somewhat lower values, which might possibly be caused by irrigation losses. These losses give an overestimate of the evapotranspiration from the water balance, which results in too low values of R_c^{ψ} .

The relation between the potential (ψ_l^{pot}) and the real (ψ_l^{re}) suction in the leaves is shown in Fig. 6. The deviation from the straight line given in this figure indicates that reductions in transpiration are already present at low suctions in the leaves.

Maturation

In maturing plant communities a substantial reduction in transpiration is present even when the crop is well irrigated and well fertilized. This is mainly caused by leaf age

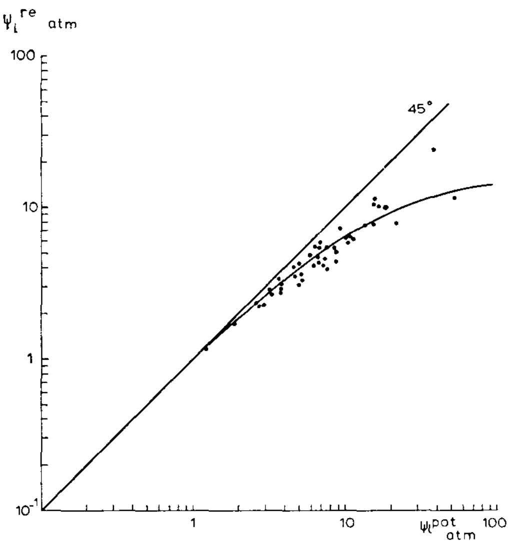

Fig. 6 Relation between the real suction (ψ_l^{re}) and the potential suction (ψ^{pot}) of the leaves for a potato crop

and the increase of the percentage of dead leaves when maturation proceeds. Estimates of the percentage of dead leaves were used to describe the course of maturation during the growth.

In the model describing the contribution of the diffusion resistance, the crop maturation was considered to have a large effect on the internal transport resistance. This was based on the argument that the dead leaves do not contribute to the transpiration process, so for a same flux per unit of soil surface the internal transport pathways are decreasing with increasing percentage of dead leaves.

The data of 1964 were used to calculate the effect of the percentage of dead leaves on the value of R_{pl}. The relation between the percentage of leaves which were still alive and the internal transport resistance is given in Fig. 7. Though the scatter of the data is rather large, it will be clear that with a decreasing percentage of living leaves below 50 % the value of R_{pl} increases considerably. The curve drawn in this figure was also used in the calculation of evapotranspiration in the other years.

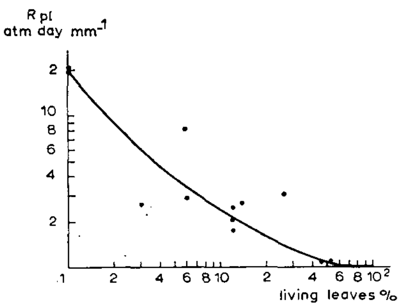

Fig. 7 The relation between the internal transport resistance of the crop (R_{pl}) and the percentage of leaves still alive, in 1964

Results and discussion

For comparison purposes, the calculated evaporation from a continuous wet crop surface (E_{wet}), the evapotranspiration obtained by Eq. 3 (E_{re}) and the one derived from the water balance (E_{wb}) are given in Fig. 8 (p. 292–296; explanation on p. 292). Moreover the total amount of precipitation and sprinkling water is given for each balance period expressed as a mean value per day, as well as the mean suction in the effective root-zone of 40 cm at each sampling date. With respect to the results a number of aspects must be discussed.

Soil cover

The curve used for the determination of the effect of soil cover on transpiration was derived from experiments performed under normal weather conditions, without preventing evaporation from the bare soil. As a consequence the results will be correct when no extreme situations in the distribution of precipitation were present. This means that systematic deviations will occur under either extremely dry or extremely wet conditions. Under extremely dry conditions the calculated values of E_{re} will be higher than those derived from the water balance when a partial soil cover is present. This is demonstrated in the results obtained from the v_0 fields in 1959, when during the first balance periods hardly no precipitation was present.
The opposite situation was present in 1963, when during the first two balance periods the distribution of precipitation was very regular, with a large number of small showers, which increased the evaporation from the bare soil. In this situation the data derived from the water balance approach the calculated value of E_{wet}. A more or less similar situation was present in 1965.
In the other years the distribution of precipitation was such that a reasonable approach during the first stages of growth was obtained.

Moisture conditions

The calculated values of E_{re} and the data from the water balance agree reasonably well. It shows that the actual transpiration rate can be calculated under practical conditions when the given relation between diffusion resistance and ψ_l^{pot} is used.
The distribution of precipitation as well as the time of irrigation within the balance periods might affect the soil moisture conditions in such a way that the real mean suction in the root-zone is much smaller than the mean value calculated from the soil moisture data at the beginning and at the end of the balance period. This situation can be particularly present on the irrigated fields, as sprinkling was applied very often one or two days after sampling, resulting in a sharp decrease in suction directly after sampling. Due to this the calculated values of E_{re} are too low at the irrigated fields. This effect increases with increasing irrigation frequency, as is clearly shown in data of 1964.
In addition to this, a small drainage to the deeper layers might be present, resulting in an overestimate of the evapotranspiration obtained from water balance data. The values derived from the water balance exceed the calculated E_{wet} data under extremely wet conditions, showing that discharge must have been present during these periods.

Maturation

The relation between the internal crop resistance R_{pl} and the amount of living leaves,

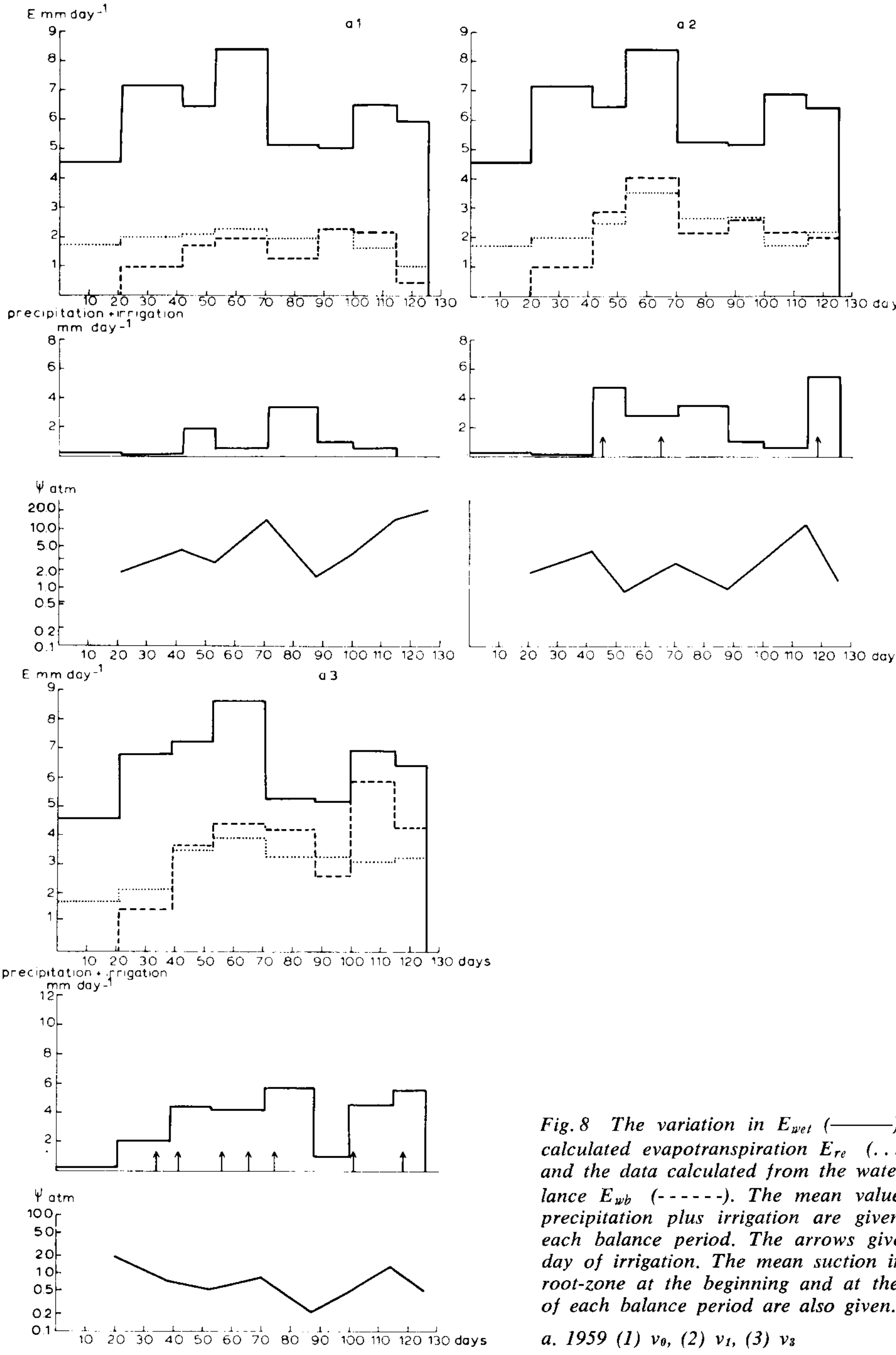

Fig. 8 The variation in E_{wet} (———), the calculated evapotranspiration E_{re} (. . . . . .), and the data calculated from the water balance E_{wb} (- - - - - -). The mean values of precipitation plus irrigation are given for each balance period. The arrows give the day of irrigation. The mean suction in the root-zone at the beginning and at the end of each balance period are also given.

a. 1959 (1) v_0, *(2)* v_1, *(3)* v_3

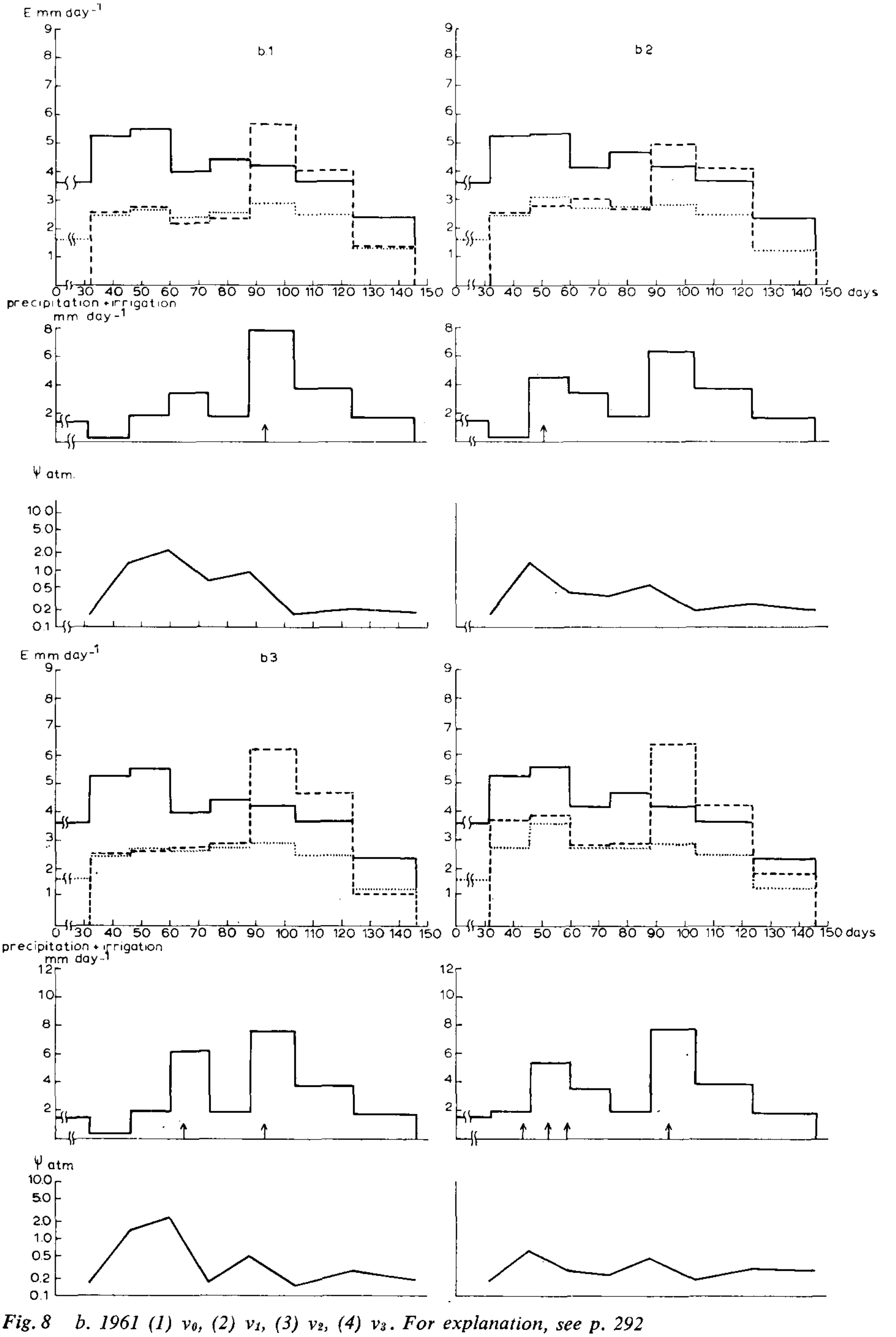

Fig. 8 *b. 1961 (1) v_0, (2) v_1, (3) v_2, (4) v_3. For explanation, see p. 292*

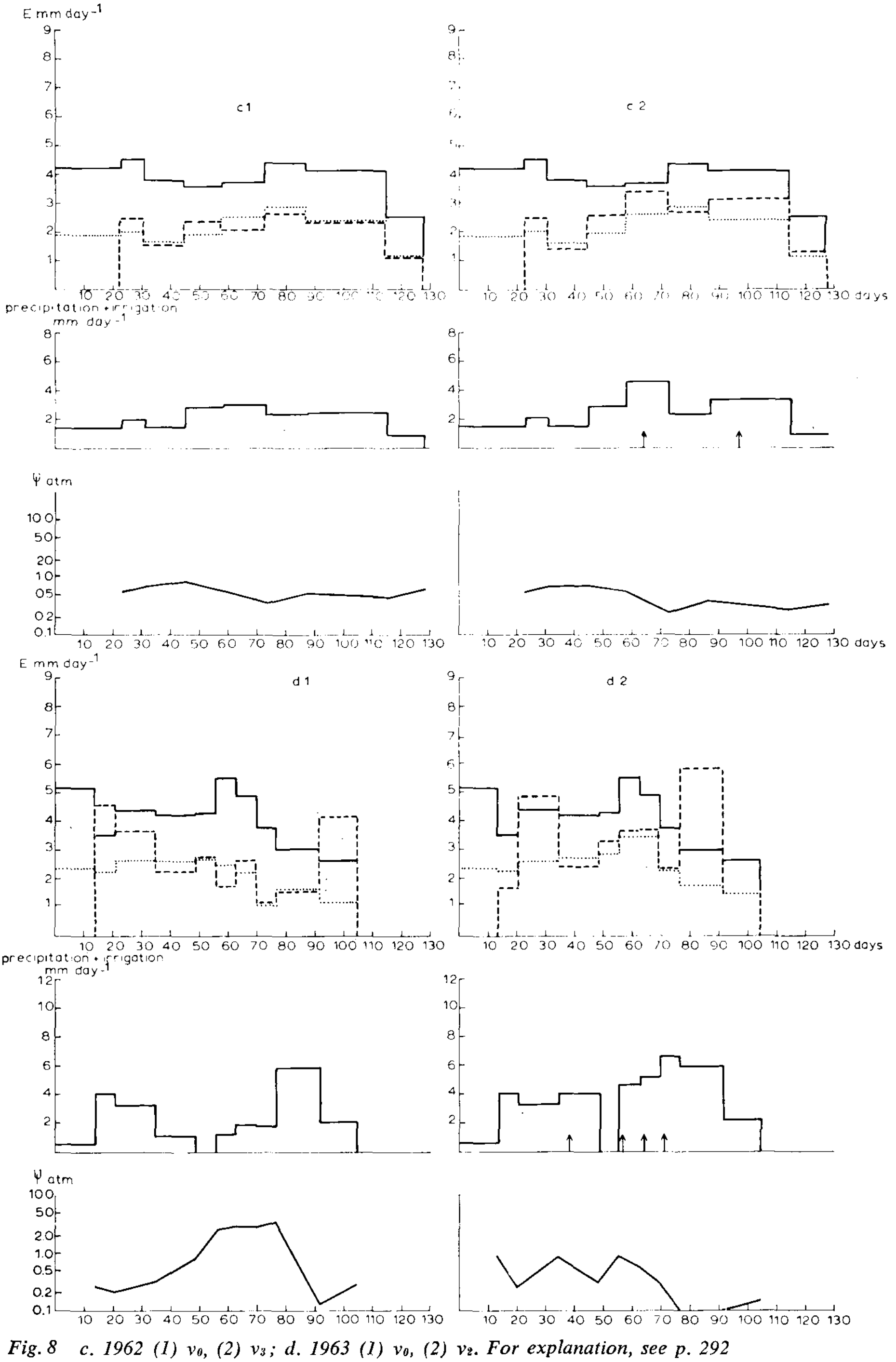

Fig. 8 *c. 1962 (1) v_0, (2) v_3; d. 1963 (1) v_0, (2) v_2. For explanation,* *see p. 292*

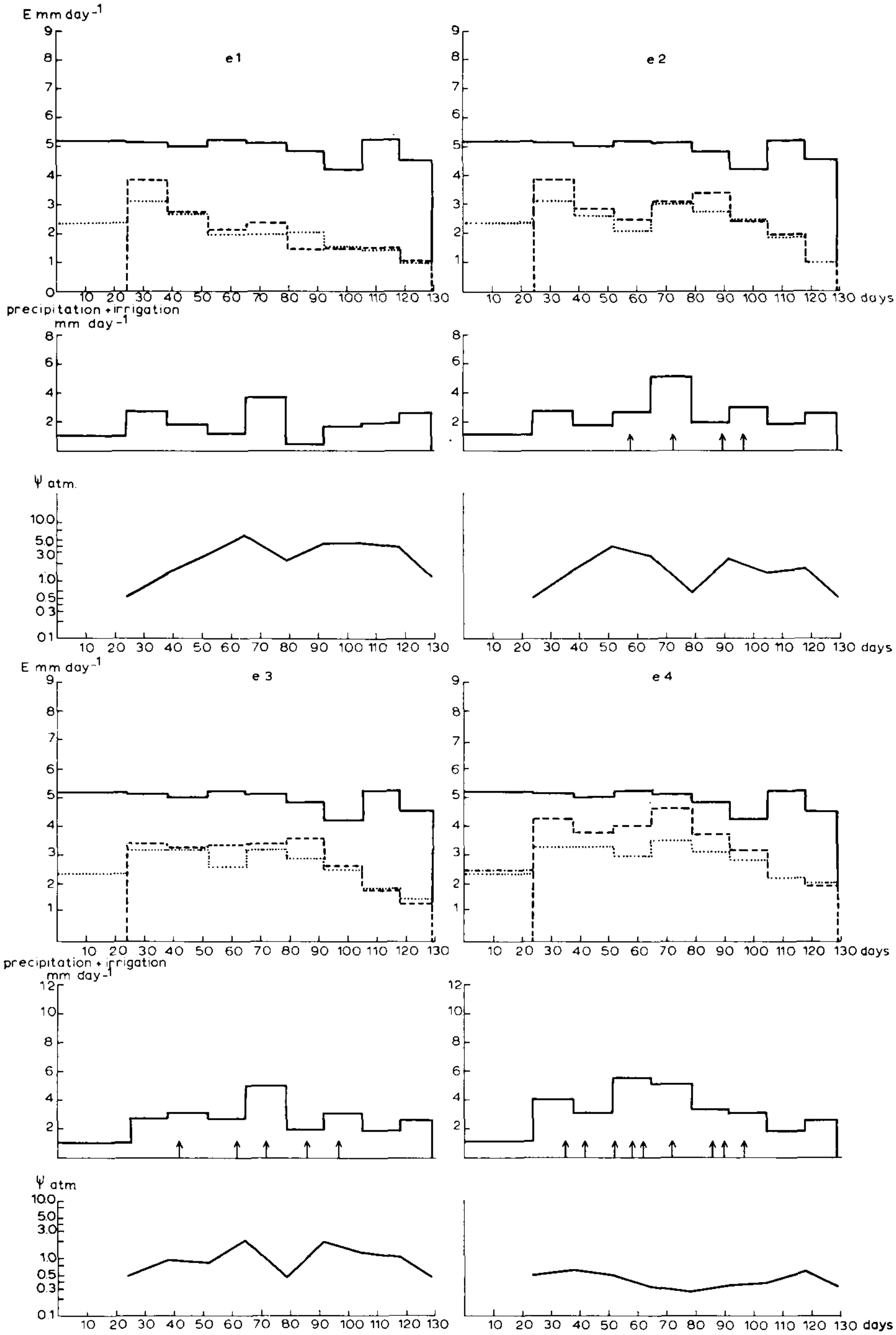

Fig. 8 ie. 1964 (1) v_0, (2) v_1, (3) v_2, (4) v_3. For explanation, *see p. 292*

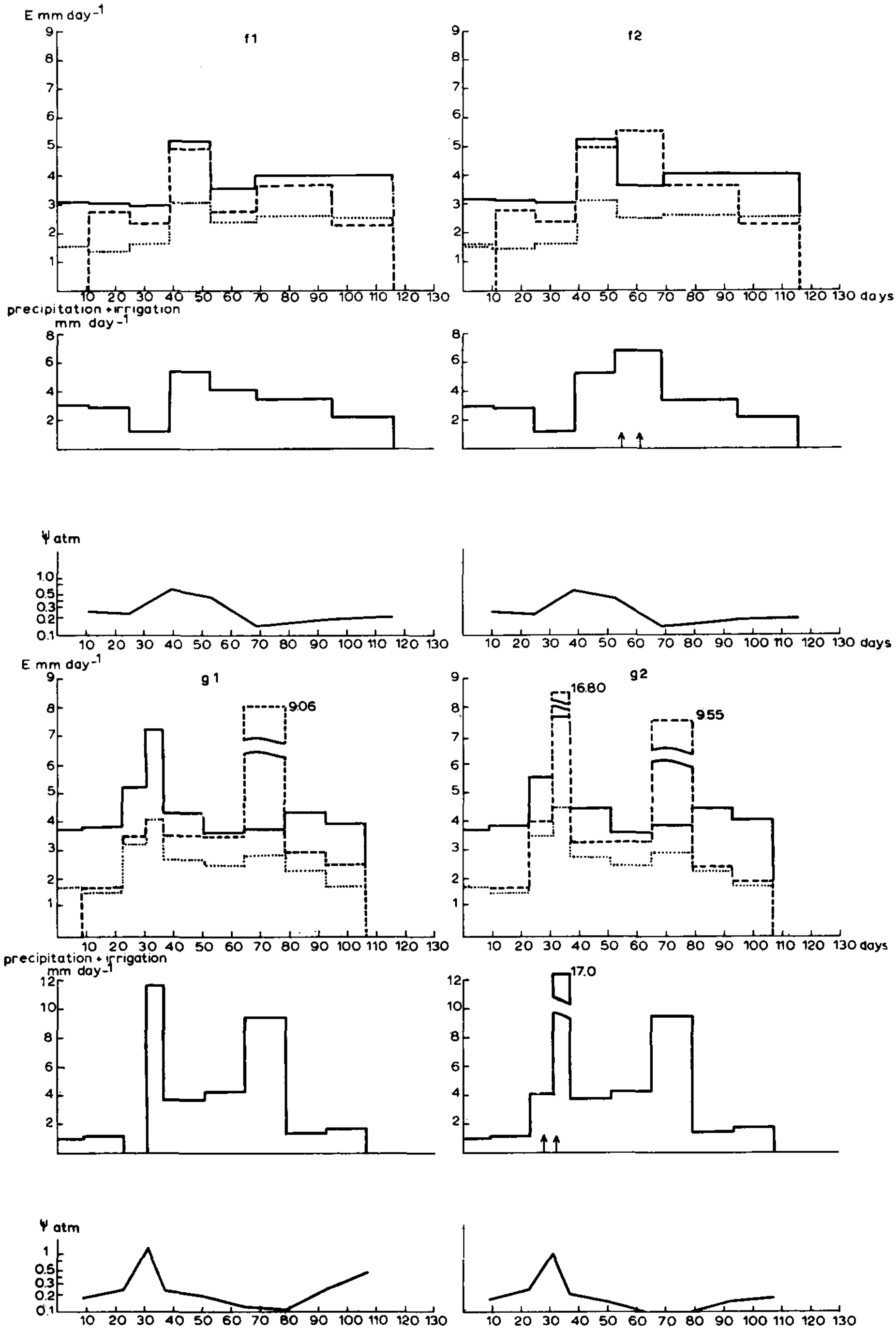

Fig. 8 *f. 1965 (1)* v_0, *(2)* v_3; *g. 1966 (1)* v_0, *(2)* v_3. *For explanation,* *see p. 292*

given in Fig. 7 for 1964 as description of maturation, did give acceptable results in all the other years when due to the proceeding of maturation large reductions in transpiration were present. It means that a fairly good approach for the effect of maturation can be obtained by increasing the value of R_{pl} in the calculation model.

Comparison with other data

Gardner and Ehlig (1963) give the relation between the relative transpiration rate $(E_T^{rc})/(E_T^{pot})$ and the mean suction in the leaves for various crops. The suction at which the transpiration rate starts to reduce varies from 4 bars for a pepper crop to 12 bars for cotton.

The relative transpiration rate of the potato crop in the present study is plotted in Fig. 9 versus the mean suction in the leaves. The figure is given for three classes of soil cover. The ratio decreases more slowly under conditions of a low soil cover than under conditions of a complete soil cover. This is mainly due to the fact that under conditions of a partial soil cover the calculated values of E_T^{pot} are much lower than for a full cover crop, so the effect of suction on transpiration becomes less.

The shape of these curves agrees well with those found by Gardner and Ehlig. However, the reduction in the transpiration starts already at 1 atm. suction, which value is much lower than the corresponding values for the crops given by Gardner and Ehlig. The main reason might be the way in which the potential transpiration rate was determined. Gardner and Ehlig did their experiment under controlled constant meteorologic

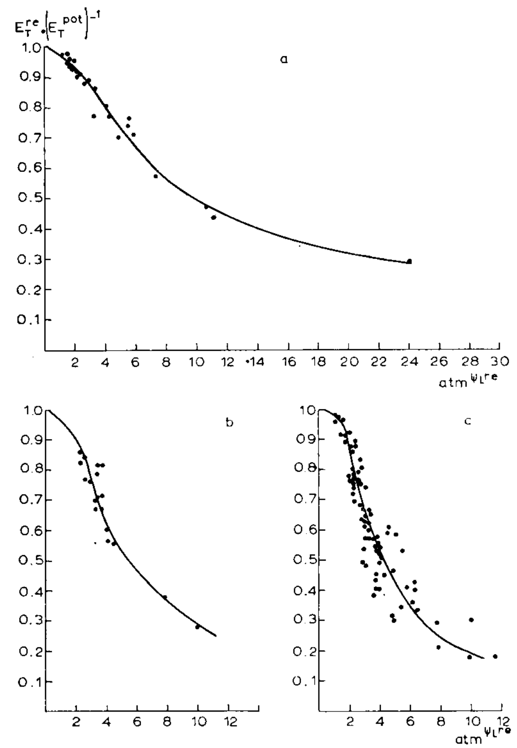

Fig. 9 The relation between the ratio E_T^{re}/E_T^{pot} and the real suction in the leaves (ψ_l^{re}) for 3 groups of soil cover. a. soil cover < 50 %; b: soil cover between 50 and 80 %; c: soil cover > 80 %

conditions and they determined the potential transpiration rate from the water balance when the crop was well supplied with water. In Fig. 9 the potential transpiration rate was calculated from the meteorologic conditions with Eq. 3 assuming that the influence of the resistances in the liquid path could be neglected. In the experiments of Gardner and Ehlig the effect of internal resistances under conditions of optimum water supply was automatically taken into account, which results in a lower value of the potential transpiration rate in their experiments than will be obtained from the calculation of the meteorologic conditions while neglecting the internal resistances as was done in the present paper.

Szeicz et al. (1969) calculated from experimental data on potatoes in Germany (Tajchman, 1967) the mean monthly resistances of the evaporating surface from the ratio of monthly totals of evaporation (LE) and the available net energy (H_{nt} - G), using an empirical relation given by Monteith (1965). This empirical expression gives the relation between surface resistance r_s in the range $0.25 < r_s < 10.00$ sec. cm^{-1}, and the ratio transpiration over available energy as:

$$\log_{10} r_s = 1.40 - \frac{2LE}{H_{nt} - G} \tag{7}$$

The surface resistances derived by Szeicz et al. (1969) with Eq. 7 from the data taken in 1965 in Germany are given in Fig. 10 in relation to the time of the year. The crop resistance of potatoes in the present study was calculated according to soil cover, light intensity and soil moisture conditions in the root-zone. These data calculated for 1965 are also presented in Fig. 10. The data from both places deviate strongly during the early stages of growth, which is mainly due to the very wet conditions in Germany when the crop was only partly covering the soil. The water balance data and those calculated for 1965, as presented in Fig. 8, did show a large deviation due to the wet conditions in this year. When the crop was completely covering the soil, identical values of this surface resistance were found at both locations. This result shows that the procedure followed in the present study leads to very acceptable values of the surface resistance.

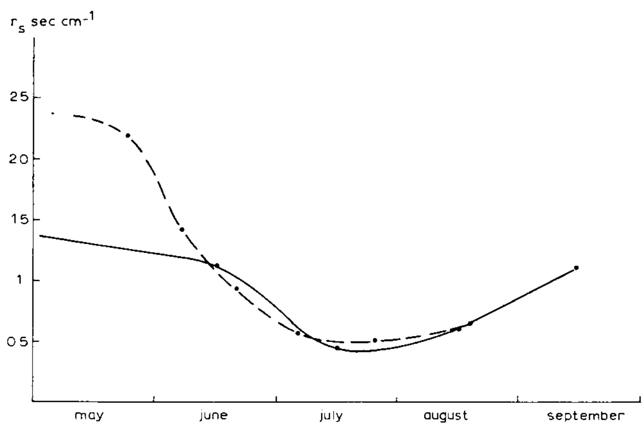

Fig. 10 Comparison of the variation in surface resistance r_s of potatoes in 1965 in the Netherlands (----) and in Germany (——) under conditions of a good water supply

The empirical approach, given by Monteith, does not give a direct evaluation of the influence of variations in crop development and in moisture conditions on the value of the surface resistance under various meteorologic conditions, which restricts the use of this relation for practical application. The present method used for the evaluation of the surface resistance has as main advantage that the value of the surface resistance is derived from data of soil cover, radiation intensity, moisture conditions and maturation. The influence of these factors can be evaluated directly from the given relations and can be applied under any given meteorologic conditions.

Conclusions

The estimated values of crop height and soil cover derived from the crop development-time curves did give acceptable results in the calculation of evapotranspiration from potatoes. The result indicates that a more or less standard crop-development curve can be used for this crop when some data are known. This is of particular importance when calculating the water use of potatoes in longterm studies.

The calculated values of evapotranspiration and the data obtained from the water balance agreed reasonably well under conditions of a limited water supply, showing that the actual transpiration rate can be calculated under practical conditions when the given relation between the diffusion resistance ($R_c{}^{\psi}$) and $\psi_l{}^{pot}$ is used.

The relation between the internal crop resistance (R_{pl}) for liquid flow in the crop and the percentage of living leaves, as used in the calculation model, did give a fair approach to describe the influence of maturation on evapotranspiration.

Due to the low values of the potential suction in the leaves at which stomatal reaction starts, large reductions in transpiration were present when under optimum conditions of soil moisture supply the evaporative demand of the atmosphere was high.

The method used for the evaluation of the diffusion resistance of the crop surface did give similar results as the empirical relation given by Monteith (1965). The method described in the present paper has as main advantage, however, that it describes the surface resistance as a function of a number of crop properties which are independent of climate.

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