Neth. J. agric. Sci. 18 (1970) 26—36

Calculation of production of potatoes

P. E. Rijtema and Gabriella Endrödi[1]

Institute for Land and Water Management Research, Wageningen, the Netherlands

Received 29 May 1969

Summary

A discussion of the net photosynthesis of a potato crop was given. It appeared to be possible to calculate the actual dry-matter production, even when water supply limited growth, using a modification of the procedure proposed by de Wit (1965).

The method proposed is very useful to evaluate the reduction in production due to drought during growth.

The relation between transpiration and total dry matter production was dependent on the meteorological conditions during growth, and not on specific differences between the varieties used in the experiments.

The distribution of dry matter over the different parts of the plants was discussed.

Introduction

The formative development of the plant is extremely important to the grower, as it determines to what extent and during which period of the year the crop is able to convert the available solar energy into photosynthetic products.

The agronomist is confronted with the problem of discovering the limits of production, considering the factors which can be affected by human agency. When analysing the productivity of field crops one should like to be informed on both maximum and actual production per unit of soil surface. As availability of water is under many conditions a limiting factor for production, special attention will be given to the effect of moisture conditions on the dry-matter production of a potato crop. The relation between transpiration and dry-matter production is particularly important with respect to irrigation practice.

The economic value of the production is largely affected by the distribution of the produced dry matter over the different organs of the plant. The parts of the plant, which are not of economic interest are in a certain sense useless lumber, but a necessity, however, to obtain good yields of the main product. In this respect some attention will be given to the distribution of dry matter over the different parts of the potato plant.

The present paper gives an attempt to calculate the maximum potato production from the meteorological conditions during the growth of the crop. Limitations in the maximum production due to moisture shortage during growth are also taken into consideration. The method proposed can be useful in a better evaluation of the reduction of the production due to drought damage during growth.

[1] *Guestworker from the Meteorological Observatory, Budapest, Hungary.*

Available data

During a number of years sprinkling irrigation experiments with potatoes were performed at the experimental farm of the Institute. A description of the available data concerning moisture content, irrigation frequency, crop development and transpiration were published in an earlier paper (Endrödi and Rijtema, 1969).
Periodical harvests over three years of the potato crop were present. These data will in particular be used to test an approach to net photosynthesis of this crop during the different stages of crop development. The plant density was about 48,000 plants per ha. The crop production was calculated for the same periods as those which were used in the study on transpiration (Endrödi and Rijtema, 1969).

Photosynthesis of a potato crop

Quantitatively, the synthesis of compounds other than carbohydrates may be ignored during the growth of a field crop. This means that dry-matter production is mainly the result of net photosynthesis. The photosynthetic process consists of several processes and for the present discussion the following remarks have to be made:

a. Photosynthesis is a photochemical process using light energy for the reduction of CO_2. This process is only influenced by light and not by CO_2 or temperature.
b. Photosynthesis is affected by a diffusion process transporting CO_2 from the external air to the chloroplasts. The rate of the diffusion process depends mainly on the CO_2 concentration in the external air and in the leaf mesophyll, as well as on the different resistances in the different pathways. Light can affect the diffusion rate indirectly through an influence on the stomatal diffusion resistance (Gaastra, 1959).
c. Photosynthesis is influenced by biochemical processes reducing CO_2 to carbohydrates. These processes are strongly affected by temperature and not by light and CO_2. The efficiency of the biochemical processes and the respiration rate of the plant determine in fact the efficiency of the production process.

The partial processes are affected in a different way by external conditions. Each of these processes may limit the production rate under field conditions, so it is necessary to take all these factors in consideration when dry-matter productions are calculated. Since light energy is the factor which can be determined with the greatest ease and accuracy, it is useful to take this variable as the main factor in a production function, while the other variables are used as correction factors.
For this reason the approach given by de Wit (1965) of photosynthesis of leaf canopies was used as basic term for the production function. De Wit's approach is mainly based on solar radiation and leaf distribution functions. For a set of standard conditions he calculated the daily photosynthetic rate for very clear days as well as for overcast ones, assuming that the light intensity on overcast days is 0.2 times the corresponding value H_c on very clear days. The light energy H_c is expressed in cal cm^{-2} day^{-1} for the range of 400 to 700 nm. Moreover, the external transport resistance r_a was assumed to be 0.5 sec . cm^{-1}. The daily photosynthetic rate under de Wit's standard conditions at latitude 52° North is given in Table 1.
The daily production rate during each period was calculated, following the procedure proposed by de Wit, as $P = F P_o + (1 - F) P_c$ kg $CH_2O . day^{-1} . ha^{-1}$, in which F, the fraction of time that the sky is clouded, is obtained from $(H_c - H_a) (0.8 H_c)^{-1}$. H_c is the mean value of the radiation on clear days and H_a the actual mean value,

Table 1 The daily totals of light (wavelengths 400–700 mμ) on very clear days (H_c) in cal.cm^{-2}.day^{-1}, the photosynthetic rate on very clear days (P_c) and on overcast days (P_o) in kg CH$_2$O ha^{-1}.day^{-1} for 52° North. r_a = 0.5 sec.cm^{-1} (after de Wit, 1965)

Date	Jan. 15	Febr. 15	March 15	Apr. 15	May 15	June 15	July 15	Aug. 15	Sept. 15	Oct. 15	Nov. 15	Dec. 15
H_c	63	119	195	295	375	416	402	337	243	151	81	52
P_c	131	209	299	404	485	526	512	446	350	247	157	114
P_o	52	92	143	203	250	274	265	227	172	113	65	43

equaling 0.5 H_{sh} where H_{sh} is the global radiation. The production calculated in this way will be considered as the potential production (P_{pot}) of a standard crop as defined by de Wit (1954, Table 5).

The calculated potential production is plotted in Fig. 1 versus the dry-matter production obtained from the periodical harvests of the frequently irrigated potato fields in 1961 (variety Libertas), 1962 (variety Surprise) and 1964 (variety Surprise). The potential production was calculated, starting from the day that the crop came up. The curves for 1961 and 1962 coincide, but the 1964 curve deviates continuously from the other one. The main reason of this deviation might be the difference in the temperature conditions during the early stages of growth, which was in 1964 about 3° C higher.

The calculation of the potential production only holds for a crop which completely covers the soil. Partial soil cover results in a waste of light available for photosynthesis during the early stages of growth. The effect of soil cover on production can be eliminated by multiplying the calculated potential production by the fraction of the surface area covered by the plants.

The values of the potential production have to be corrected in relation to the effect of the different resistances in the diffusion pathway. De Wit estimated the effect on photosynthesis of the exchange resistance r_a between the bulk air and the effective canopy surface. The data of the exchange resistance r_a and the production in kg CH$_2$O.ha^{-1}.h^{-1} are given in Table 2. The relative production rate with respect to the

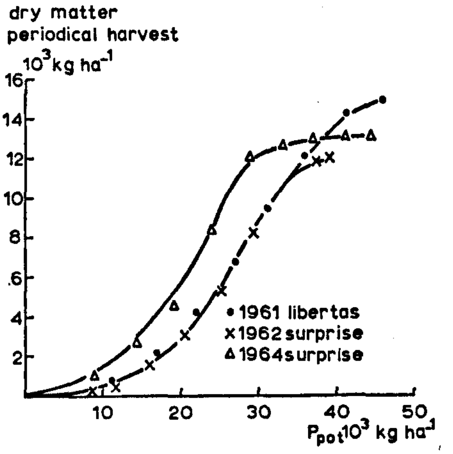

Fig. 1 The relation between calculated potential production and the data obtained from periodical harvests

Table 2 The external resistance r_a, the corresponding production rate, the relative production rate and the ratio of the total resistances

r_a (sec . cm^{-1})	P (kg CH_2O . ha^{-1} . h^{-1})	Relative production	$\frac{0.5 + 4.4}{r_a + 4.4}$
0.25	42.3	1.05	1.05
0.50	40.3	1.00	1.00
1.00	37.4	0.93	0.91
1.50	34.4	0.85	0.83
2.00	31.2	0.77	0.77

production when $r_a = 0.5$ sec . cm^{-1} is also presented. Assuming that the sum of the surface resistance (r_s') and the mesophyll resistance (r_m') of the canopy equals under these conditions 4.4 sec . cm^{-1}, than the corresponding ratio of the total sum of resistances with respect to $r_a = 0.5$ sec . cm^{-1} is presented in the last column of Table 2.
It appears from Table 2 that the production rate at other values of the external transport resistance r_a can be approximated as:

$$P = \frac{0.5 + 4.4}{r_a + 4.4} P_{pot} \tag{1}$$

It has been shown (Rijtema, 1965) that the surface resistance of some crops, with respect to transpiration equals to zero under conditions of high light intensity and optimum water supply. As the diffusion coefficients of H_2O and CO_2 differ considerably, it is not necessarily a consequence that for these crops the surface resistance for CO_2 diffusion also equals zero. When production calculated by de Wit's method is considered as the potential one, it must follow that the given value of 4.4 sec . cm^{-1} gives a minimum value of the sum of r_s' and r_m'. In the further discussion this value of 4.4 sec . cm^{-1} will be indicated for convenience as r_m', but it must be kept in mind that it partly includes a stomatal term.
For the potato crop under consideration it has been shown (Endrödi and Rijtema, 1969) that even under optimum conditions of water supply the surface resistance for transpiration is not equal to zero, indicating also a higher surface resistance value for CO_2 transport. This surface resistance value is calculated as:

$$r_s' = (D_{H_2O}/D_{CO_2}) \cdot r_s \tag{2}$$

where r_s' is the surface resistance for CO_2 transport, D_{H_2O} and D_{CO_2} the diffusion coefficients of H_2O and CO_2, respectively, and r_s the surface resistance determined from the transpiration data, taking into account only the light depending term and the suction dependent term, as the soil cover term has been eliminated already.
The production rate can be expressed under these conditions by the equation:

$$P = \frac{0.5 + 4.4}{r_a + r_s' + 4.4} \cdot s_c P_{pot} \tag{3}$$

where s_c is the fraction of soil cover.

References presented by Bierhuizen en Slatyer (1964) show that the photosynthetic ef-

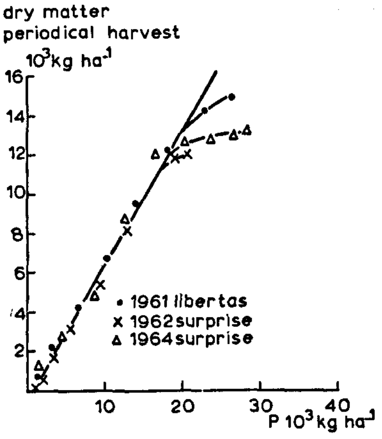

Fig. 2 The relation between production calculated with Eq. 3 and the data obtained from periodical harvests

ficiency depends on plant species and temperature. De Wit's method ignores production losses from respiration. Assuming that the respiration rate is proportional to the production rate, this offers the opportunity to give the reduction in production by an efficiency factor a.

Under these conditions the actual production (P_a) can be given as

$$P_a = a \frac{0.5 + 4.4}{r_a + r_s' + 4.4} \cdot s_c P_{pot} \tag{4}$$

The dry-matter production derived from the periodical harvests is plotted in Fig. 2 versus the calculated production according to Equation 3. The data give a linear relation, showing that the efficiency factor a for the potato crops under consideration equals 0.68, when the production of the standard crop as given by de Wit is taken as a norm.

The deviation from linearity at the end of the growing season is mainly due to the effect of the increasing number of dead leaves, which do not participate in the photosynthetic process. This affects production in two ways. Firstly the internal resistance of the canopy as a whole increases, and secondly it causes a reduction in the photosynthetic efficiency of the complete canopy is reduced, perhaps partly through an increased respiration rate.

With use of the curves drawn at the end of the growing season an estimate has been made of both effects by means of an iterative procedure. The estimated influence of dead leaves on the internal resistance is presented in Fig. 3, showing a gradually increasing effect on the value of the internal canopy resistance. The effect of dead leaves on the photosynthetic efficiency is given in Fig. 4.

The calculated production on fields with a limited water supply must agree with the results obtained from periodical harvests, if the approach, given in Equation 4 for the calculation of production is correct. This has been tested for irrigated fields (v_1: irrigation after 75 % moisture extraction; v_2: after 50 %; v_3: after 75 %) and for a field without irrigation (v_0), and the results were compared with the data derived from the periodical harvests in 1964. Reduction in transpiration (Endrödi and Rijtema, 1969) caused wide variation in the value of r_s'. Moreover, the distribution of the number of

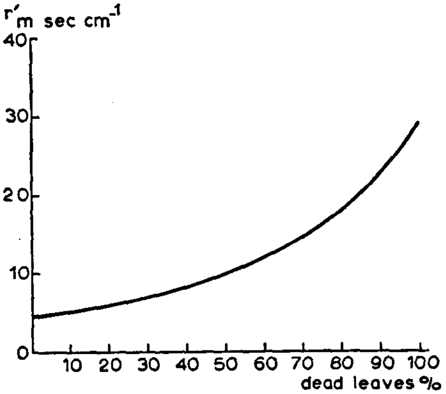

Fig. 3 The estimated relation between internal diffusion resistance and percentage of dead leaves in the canopy

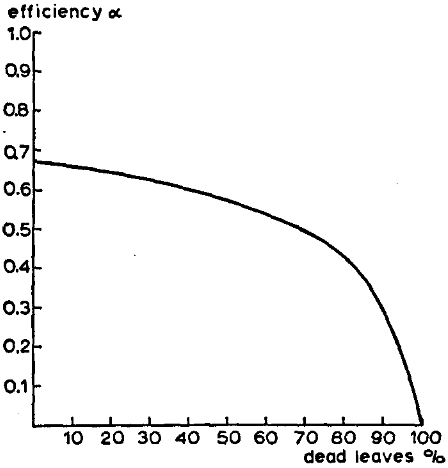

Fig. 4 The estimated relation between photosynthetic efficiency and percentage of dead leaves in the canopy

dead leaves differed considerably in time from the corresponding data of the frequently irrigated field, having its consequences in the calculations. The comparison of the calculated data with those obtained from periodical harvests is presented in Fig. 5. The data of the frequently irrigated field in 1961, 1962 and 1964 are also given. The agreement between the dry-matter production according to the periodical harvest and the calculated one is good, indicating that a fair approach of the dry-matter production of potatoes can be obtained, even when moisture conditions are limiting.

Transpiration and dry-matter production

The relation between transpiration and dry-matter production is of particular interest for irrigation practice, since the optimum effective irrigation gifts with respect to the production can be determined from this relation. The evaporation of intercepted precipitation, however, affects this relation, as the evaporation (E_I) due to precipitation reduces the transpiration rate. Rijtema (1969) gives an approach to eliminate this effect, using the expression

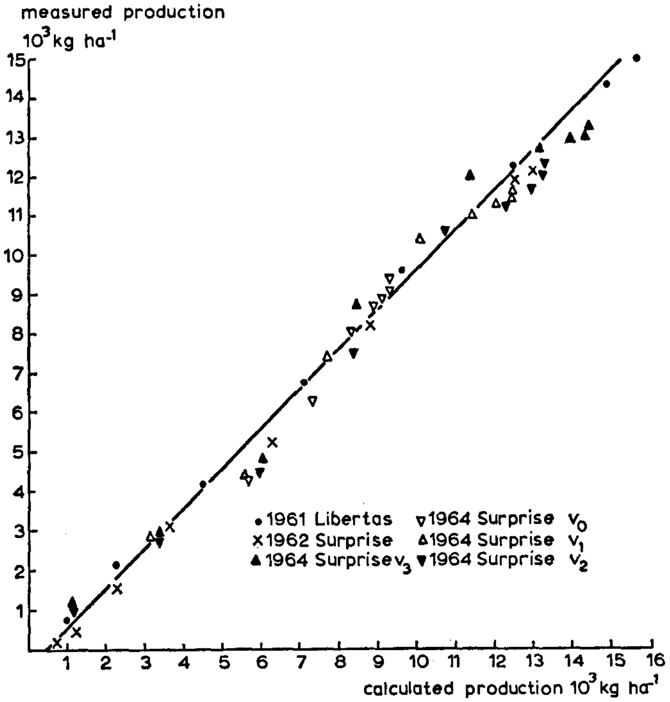

Fig. 5 The relation between calculated actual production with Eq. 4 and the data obtained from periodical harvests

$$E_T^{re} = \frac{E_{wet}}{E_{wet} - E_I} \cdot (E_{re} - E_I) \tag{5}$$

where $\dot{E}_T^{re}$ is the transpiration rate from the crop, when E_I equals zero, E_{wet} the evaporation rate when the crop surface is continuously wet and E_{re} the calculated real evapotranspiration.

De Wit (1958) concludes that, under the humid meteorological conditions in the Netherlands, production and transpiration are both mainly determined by radiation, so the relationship must be linear between dry-matter production and transpiration, as far as no other factors become limiting for crop growth.

The relation between total dry-matter production and the values of $\dot{E}_T^{re}$ derived from the transpiration data given by Endrödi and Rijtema (1969) is presented in Fig. 6. The scatter in the data is very large, which is partly due to the different meteorological conditions and to varietal differences.

It appeared from the preceding discussion on the photosynthesis of the potato crop, however, that the diffusion process highly affects the dry-matter production. Considering the diffusion process as the limiting factor for production Bierhuizen and Slatyer (1965) and Rijtema (1966) showed that a linear relationship between the total dry-matter production and the ratio transpiration over mean vapour pressure deficit (ε_a — e_a) can be expected, which is independent of the meteorological conditions. The

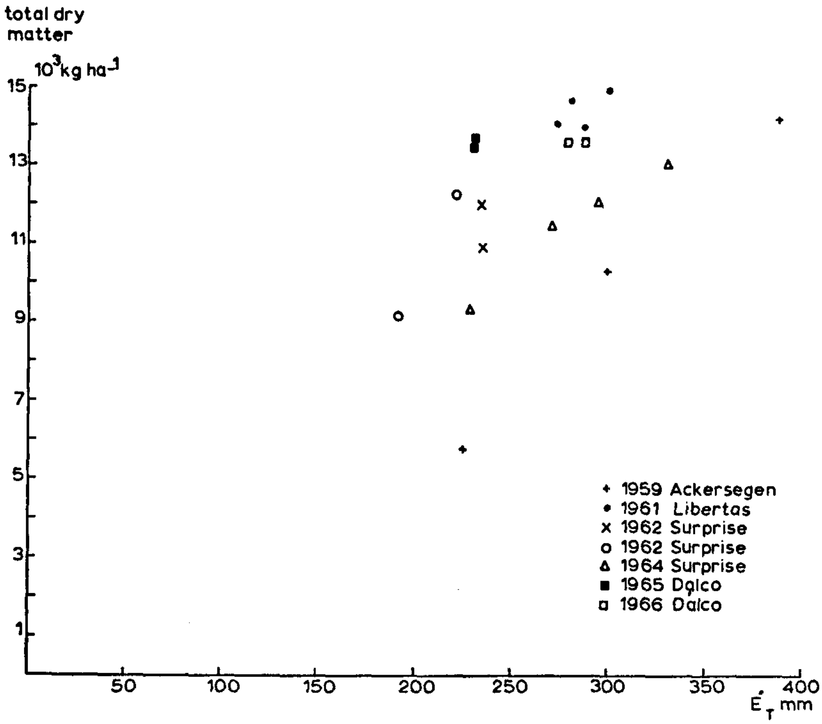

Fig. 6 The relation between transpiration and total dry-matter production

relation between total dry-matter production and the ratio transpiration over vapour pressure deficit is presented in Fig. 7. The results in this figure show that the scatter in the data in Fig. 6 is mainly due to differences in meteorological conditions in different years.

The relation between dry-matter production and the ratio transpiration over vapour pressure deficit appears to be practically independent of the potato variety used in the experiments in different years.

The somewhat deviating results obtained from the irrigated fields under the extreme dry conditions in 1959, can be mainly explained by the procedure used for the determination of the mean suction in the root zone of the crop (Endrödi and Rijtema, 1969). Large amounts of irrigation water were given a few days after soil sampling, while the mean suction during the different balance periods was determined from the soil sampling data. Due to this procedure the mean suction was seriously overestimated, which resulted in an underestimate of the real transpiration rate.

Distribution of dry matter

Though the total dry matter present at harvest gives a good indication of the growing conditions, the farmer will be much more interested in the yield of those parts of the plant which are of economic interest. This yield, however, depends closely on the distribution of dry matter over the different parts of the plant. Fig. 8A shows the relation

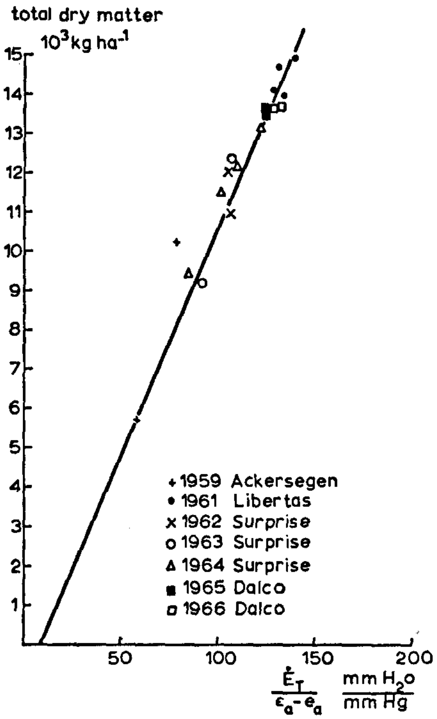

Fig. 7 The relation between total dry-matter production and the ratio transpiration over vapour pressure deficit

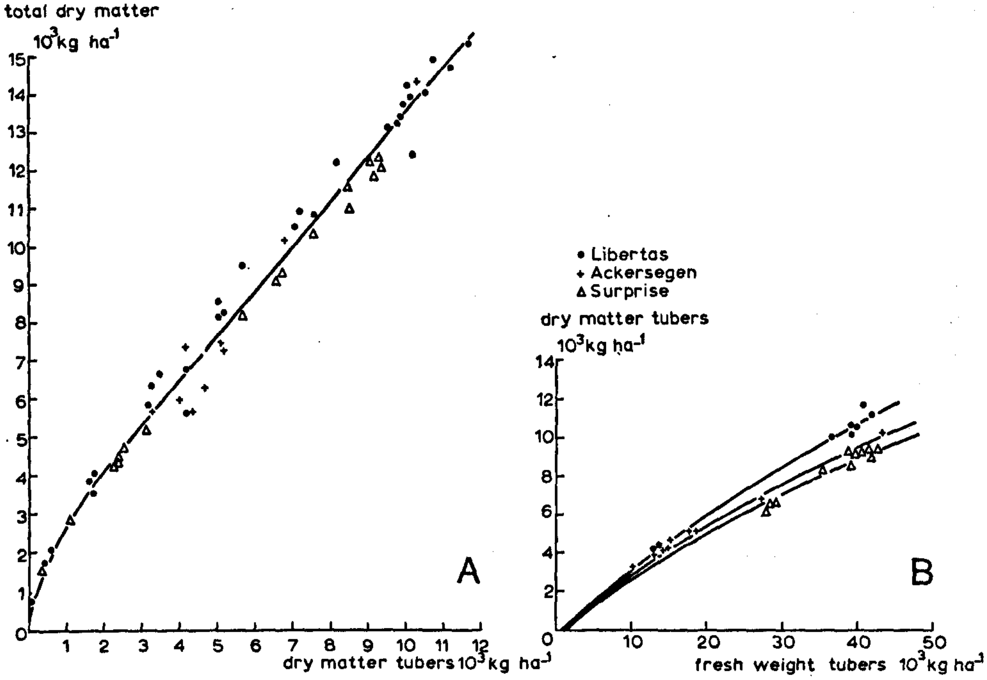

Fig. 8 A. The relation between total dry-matter production and dry matter present in the tubers; B. The relation between dry-matter production of tubers and fresh-weight yield

between total dry matter and dry matter in the tubers of different varieties. The data presented in this figure were obtained from periodical harvests and from some other experiments on timing of irrigation. The relationship is linear in the range of practical importance. Small differences between the varieties might be present but the scatter in the data is such that the relationship can be generalized for practical purposes. The scatter in the data of the variety Ackersegen, which were obtained from the irrigation timing experiments, show that the moisture conditions in the early stages of growth determine to a great extent the amount of dry matter present in the canopy.

The relation between dry matter present in the tubers and the fresh-weight production of the tubers is presented in Fig. 8B. This relation is different for the given varieties. The high level of dry-matter production of the variety Libertas which was obtained in these experiments did not result in a similar high level of fresh-weight yield, but in an increased dry-matter content of the tubers. It will be clear from Fig. 7 and 8 that the relation between these factors depends on the variety used when the effect of transpiration on fresh-weight yield is determined.

It must be taken into account, however, when the effects of drought on the potato yield are determined, if the crop was grown either for industrial purposes or for human consumption. In the first case the dry-matter production gives a better indication of drought damage, whereas the fresh weight yield it does in the latter case.

Conclusions

The method for the calculation of photosynthesis of leaf canopies, as proposed by de Wit, gives a fair approach to the production of a potato crop, when modifications are applied. These modifications include the effect on photosynthesis of soil cover, of the resistances in the CO_2 diffusion pathway and of the efficiency of the crop with respect to respiration.

The diffusion process highly affects the dry-matter production, particularly at the end of the growing season, when the number of dead leaves increases considerably.

The proposed modified method does give a good approximation of the actual dry-matter production, also when water supply was a limiting factor for growth.

The relation between dry-matter production and transpiration depends on the meteorological conditions during growth.

The linear relation between dry-matter production and the ratio transpiration over vapour pressure deficit is independent of the meteorological conditions. Varietal differences did not affect this relationship.

Differences in the maximum production of the varieties is mainly determined by the length of the growing season.

For practical purposes a linear relationship can be given between total dry-matter production and the dry matter present in the tubers. This relationship holds for all three varieties investigated.

The relation between dry-matter production and fresh-weight yield of the tubers depends on the variety.

References

Bierhuizen, J. F. & Slatyer, R. O., 1964. Photosynthesis of cotton leaves under a range of environmental conditions in relation to internal and external diffusive resistance. *Aust. J. biol. Sci.* 17: 348–359.

Bierhuizen, J. F. & Slatyer, R. O., 1965. Effect of atmospheric concentration of water vapour and CO_2 in determining transpiration – photosynthesis relationships of cotton leaves. *Agric. Met.* 2: 259–270.

Endrödi, G. & Rijtema, P. E., 1969. Evapotranspiration from potatoes. *Inst. Ld Wat. Mgmt Res. Nota* 497.

Gaastra, P., 1959. Photosynthesis of crop plants as influenced by light, carbondioxyde, temperature and stomatal diffusion resistance. *Meded. LandbHogesch.* 59: 13.

Rijtema, P. E., 1965. An analysis of actual evapotranspiration. *Agric. Res. Rep.* 659: 1–107.

Rijtema, P. E., 1966. Transpiration and production of crops in relation to climate and irrigation. *Tech. Bull. Inst. Ld Wat. Mgmt Res.* 44.

Rijtema, P. E., 1969. On the relation between transpiration, soil physical properties and crop production as a basis for water supply plans. *Tech. Bull. Inst. Ld Wat. Mgmt Res.* 58.

Wit, C. T. de, 1958. Transpiration and crop yields. *Versl. Landbouwk. Onderz.* 64.6.

Wit, C. T. de, 1965. Photosynthesis of leaf canopies. *Agric. Res. Rep.* 663: 1–57.