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# PROGRAM SIMCROP - CALCULATION OF AGRICULTURAL CROP PRODUCTION AND INCOME ON A REGIONAL LEVEL

ing. E.P. Querner and dr. R.A. Feddes

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# 1. INTRODUCTION

Regional water management plays an important role in agricultural crop production. If certain changes in water management take place, then the question arises, what is the effect of these changes on agricultural crop production in a region. In connection with this : what is the effect on net income. It is well known that under conditions of water shortage a crop will show a reduction in transpiration and hence in crop production. If one is able to determine the relationship between transpiration and crop production it will be possible to evaluate the effect of water use on crop production. Effects of ground- and open water level manipulation can then be translated into effects on crop production, by means of the intermediate variable of transpiration.

To simulate agricultural crop production one needs to be informed about actual transpiration. Crop transpiration depends on the development stage, meteorological and soil water conditions. For the calculation of transpiration a hydrological model is required. For certain situations such a model is required, because water level manipulations can have different effect within an area. In some parts of the area it can have a positive effect, in other parts a negative effect on crop production. For instance groundwater extraction decreases groundwater levels and lowers the soil water in the root zone. Drier soil water conditions results in less evapotranspiration and hence lower crop production. It is also possible that the occurrence of water logging can be decreased by the reduction in soil water resulting in higher transpiration rates and crop production. Therefore the calculation of crop production for a region should be based on results of a regional hydrological model.

An outline of the model SIMCROP ( Simulation of crop production and calculation of income ) is given in Chapter 2. In Chapter 3 the general theory on crop production is presented and also yield reduction due to nitrogen supply. In Chapter 4 the income obtained through the agricultural production is discussed. In Chapter 5 calculated results are shown of sprinkling and other water management senarios.

## 2. OUTLINE OF CROP PRODUCTION MODEL

For the simulation of agricultural crop production actual transpiration data are required. The transpiration of a crop depends on the development stage of that crop, meteorological and soil water conditions. A hydrological model, in this case FEMSATP, is taken yielding evapotranspiration results. In principle, however any other model that calculates transpiration or evapotranspiration rates can be taken. In the case of evapotranspiration values partitioning in transpiration and soil evaporation is required. The model FEMSATP computes the regional water movements in both the saturated and unsaturated zone.

The saturated zone model consists of a finite number of elements with quasi three-dimensional flow. This means a schematization into vertical flow in aquitards and horizontal flow in aquifers ( QUERNER, 1984, part 1 ). To save on computational efforts the region to be modelled is subdivided into subregions, each having relative homogeneous soil properties and hydrological conditions. Each subregion is further subdivided into different areas that are characterized by its land-use denoted as technologies.

The model of the unsaturated zone has a relative simple approach to simulate the water behaviour. Two reservoirs are present, one for the root zone and one for the subsoil, being the part between the root zone and the groundwater level. For the root zone a water balance is calculated taking the equilibrium soil water content as a maximum. The inflows from this reservoir are natural rainfall, artificial rainfall, i.e. sprinkling, evapotranspiration, and capillary rise/percolation. If the equilibrium soil water content is exceeded, then percolation occurs, otherwise capillary rise takes place. From the water balance of the subsoil the change in groundwatertable depth is calculated, using a storage coefficient that is dependent on the depth of the groundwater level. Potential evapotranspiration is reduced according to the relative soil water content in the root zone. For a detailed description of the hydrological model FEMSATP see QUERNER and VAN BAKEL ( 1984 ).

Actual evapotranspiration is the main link between the hydrological model FEMSATP and the crop production model SIMCROP. Evapotranspiration rate as calculated in the hydrological model is partitioned over transpiration and soil evaporation as a function of leaf area index.

A crop production model that quantifies the effects of water management on dry matter crop yield has been developed by FEDDES, KOWALIK and ZARADNY ( 1978 ). They have given a mathematical formulation of crop growth rate as a hyperbolic function of ( normalized ) transpiration. The production of a crop each day depends on a water use efficiency factor and the potential growth rate during that day, being mainly determined by solar radiation.

Crop parameters have been derived mainly by taking measurements in the field over a number of years. Ideally such production models should be applied separately for each type of crop. Unfortunately the parameters have not been determined for all crop species sofar. Therefore the estimation of the agricultural production for a region has been based mainly on the production of potatoes. For potatoes long year experiments are available and the model has been verified extensively ( FEDDES, WESSELING and WIEBING, 1984 ). Therefore the yield for other crops is related to the production of potatoes.

For each technology in a subregion the potential and actual yield is calculated. Subsequent this yield is corrected for differences in nutrient supply. At least the yields that theoretically can be obtained are multiplied by a factor to reach yields found in practice. In Fig. 1 a flow chart of the crop production method performed in the model SIMCROP is shown.

From the agricultural yield the income is calculated. The income is based on a fixed market price per technology and all costs directly related to the production of a crop.

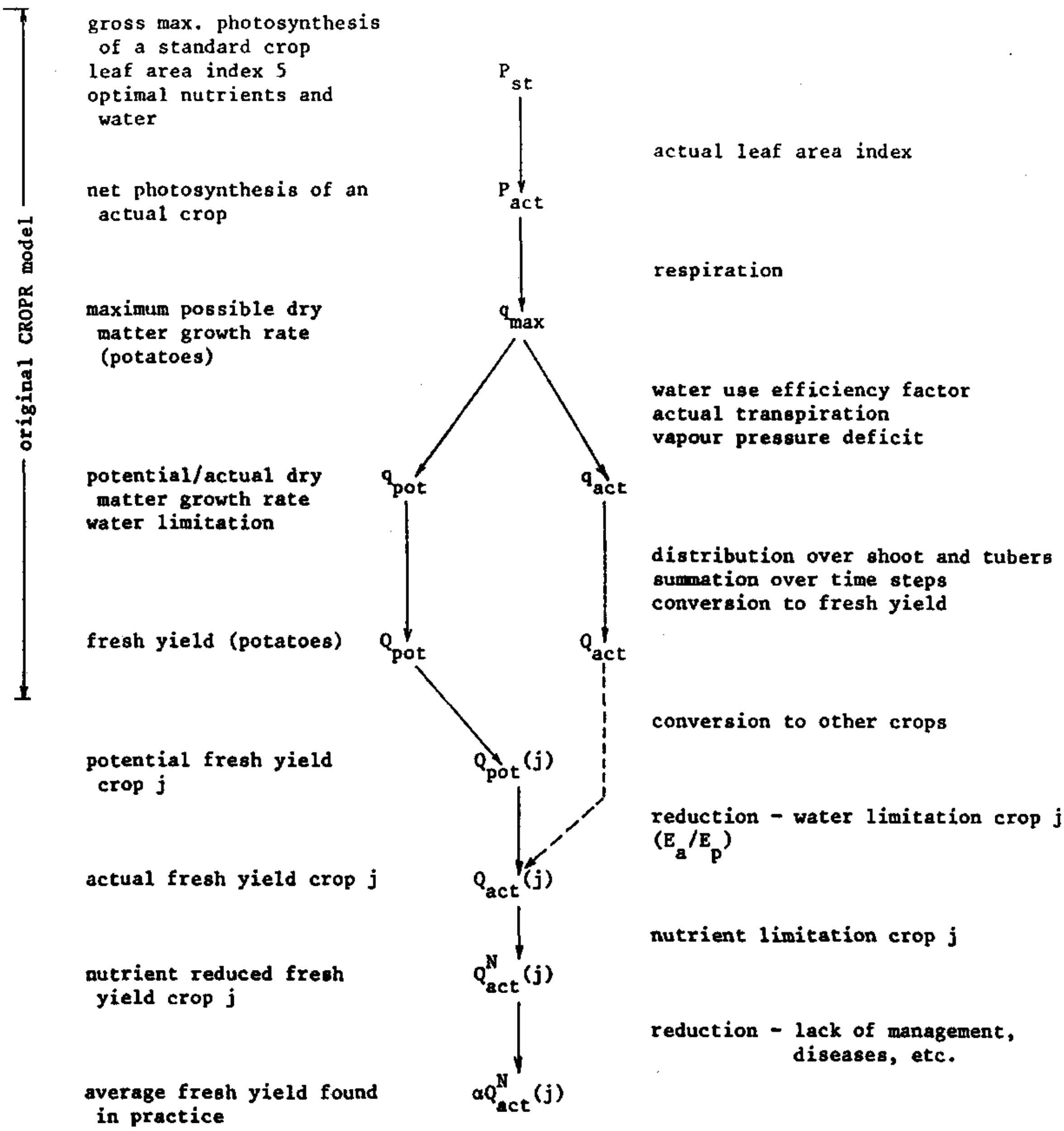


Figure 1 - Flow chart of calculation method to derive at crop productions per technology

## 3. CALCULATION OF CROP PRODUCTION

### 3.1. General theory

To estimate crop production FEDDES et al. ( 1978 ) gives a mathematical derivation of crop growth as a hyperbolic function of the growth factor water with the maximum growth rate as the upper limit and the efficiency of utilization of this factor as the initial slope of the hyperbola ( Fig. 2 ).

Daily actual dry matter growth rate $q_{act}$ having optimal nutrient supply can be calculated as ( FEDDES et al, 1978 ) :

$$\left(1 - \frac{q_{act}}{A\ T/\overline{\Delta e}}\right)\left(1 - \frac{q_{max}}{q_{max}}\right) = \zeta \qquad (1)$$

where A is the maximum water use efficiency determined from field experiments, T is the transpiration rate, $\overline{\Delta e}$ is the average vapour pressure deficit of the air, $q_{max}$ is the maximum possible growth rate, and $\zeta$ is a mathematical parameter. The relationship is depicted in Fig. 2.

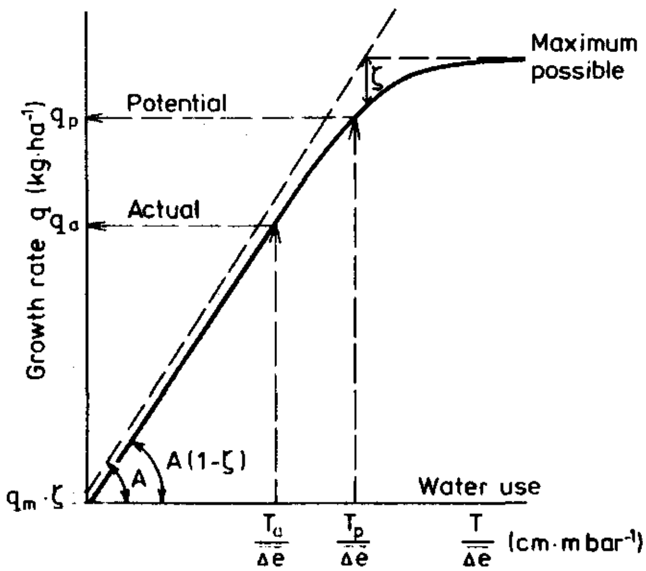


Figure 2 - Actual growth rate versus the growth factor water described as a non-rectangular hyperbola

The maximum possible growth rate is derived from the gross maximum photosynthesis rate of a 'standard' canopy. A 'standard' canopy is defined as a canopy with a leaf area index 5 ( 5 $m^2$ of leaves per square metre of soil surface ) which is fully supplied with water and nutrients. Under actual field conditions these maximum growth rates will never be reached and corrections are made to derive the actual growth rate. The calculation of maximum possible, potential and actual crop production is given in the following two paragraphs.

### 3.1.1 Maximum possible growth rate

The gross maximum photosynthesis rate $P_{st}$ of a 'standard' canopy with leaf area index I = 5 ( ha leaves/ha soil area ) that is fully supplied with water and nutrients can on any day and place at earth be found as :

$$P_{st} = P_o + (1-\lambda)\ P_c \qquad (kg.CH_2O.ha^{-1}.d^{-1}) \tag{2}$$

where $\lambda$ is the fraction of time the sky under the actual conditions is overcast, $P_o$ and $P_c$ are the gross photosynthesis rate of a standard canopy on an overcast respectively a clear day. The value of $\lambda$ can be found from the expression :

$$\lambda = \frac{R_c - 0.5\ R_s}{0.8\ R_c} \tag{3}$$

where $R_c$ is the part of solar radiation flux that is involved in photosynthesis on clear days ( 0.4 - 0.7 µm ), and $R_s$ is the short wave global radiation flux. The daily totals for $R_c$, $P_o$ and $P_c$ for various times of the year and at different latitudes have been calculated by GOUDRIAAN and VAN LAAR ( 1978 ). The annual variation at 52$^o$ north latitude ( The Netherlands ) is shown in Fig. 3.

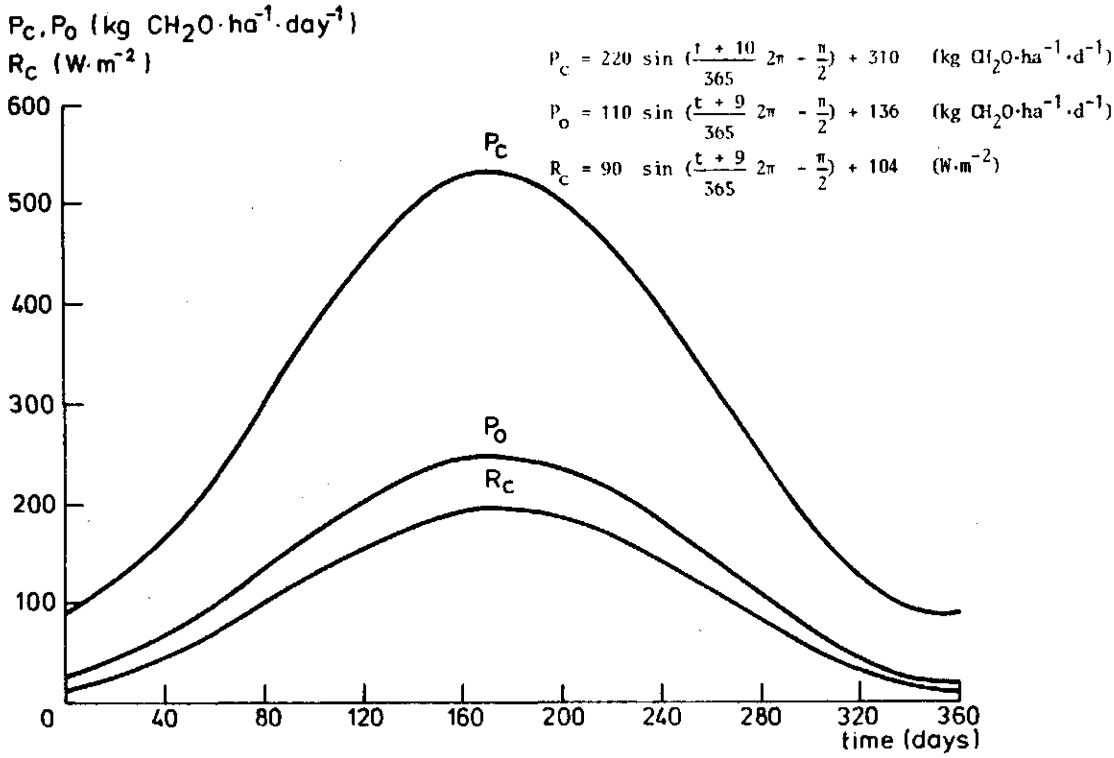


Figure 3 - Annual variation of gross photosynthesis for The Netherlands ( standard canopy )

For an actual crop with leaf area index smaller than 5 an exponential extinction of photosynthetic radiation can be assumed, and gross photosynthesis can be expressed as :

$$P_{act} = P_{st}(1-e^{-\gamma I}) \qquad (kg.CH_2O.ha^{-1}.d^{-1}) \qquad (4)$$

where I is the leaf area index and $\gamma$ is the radiation extinction factor ranging from 0.6 to 0.8.

Part of the assimilated carbohydrates, $CH_2O$, will be utilized for maintenance respiration and growth respiration. Maintenance respiration $X_m$ is proportional to dry matter weight and strongly dependent on temperature, such that :

$$X_m = 0.01\ Q_t\ 2^{(T-25/10)} \qquad (kg.CH_2O.ha^{-1}.d^{-1}) \qquad (5)$$

where $Q_t$ is the total potential yield of potatoes ( shoot and tubers ) and T is the air temperature. Growth respiration can be accounted for by a simple efficiency factor c of converting carbohydrates into structural plant material ( c $\simeq$ 0.7 ). The maximum possible dry matter growth rate can now be expressed as :

$$q_m = [P_{st}(1-e^{-\gamma I}) - X_m]\ c \qquad (kg.DM.ha^{-1}.d^{-1}) \tag{6}$$

### 3.1.2 Potential and actual production

When solving eq. (1) for the actual dry matter growth rate $q_{act}$ and actual transpiration rate $T_a$, one obtains :

$$q_{act} = 0.5\left[A\frac{T_a}{\Delta e} + q_{max} - \left\{\left(q_{max} + A\frac{T_a}{\Delta e}\right)^2 - 4\ q_{max}\ A\frac{T_a}{\Delta e}(1-\zeta)\right\}^{0.5}\right] \qquad (kg.DM.ha^{-1}.d^{-1}) \tag{7}$$

In a similar way one can calculate potential growth rate $q_{pot}$ at potential transpiration rate $T_p$.

The development of a crop with time varies from year to year, depending on environmental conditions such as temperature, day length, soil water content in the root zone, etc. Therefore a dimensionless development stage $D_s$ of a crop has been introduced as :

$$D_s = \frac{t - t_e}{t_h - t_e} \tag{8}$$

where t is the time considered, $t_e$ is the emergence date and $t_h$ is the harvest date. When $t_e$ and $t_h$ are known, $D_s$ can be computed for each value of t.

## 3.2. Yield of potatoes

The maximum water use efficiency factor, A, required in Eq. (7) for potatoes has been determined from field experiments. In Appendix B this factor is given for the years 1970 to 1981.

Analysis of long year field experiments of two different potato varieties showed that variation of soil cover $S_c$ with the development stage is approximately constant over the years ( Fig. 4a ). Because their exists a fixed relationship between the leaf area index I ( ha leaves/ha soil ) and fraction of soil cover $S_c$ :

$$I = 2.6\ S_c + 1.5\ S_c^2 + 0.9\ S_c^3 \tag{9}$$

one can link soil cover to leaf area index at various crop development stages.

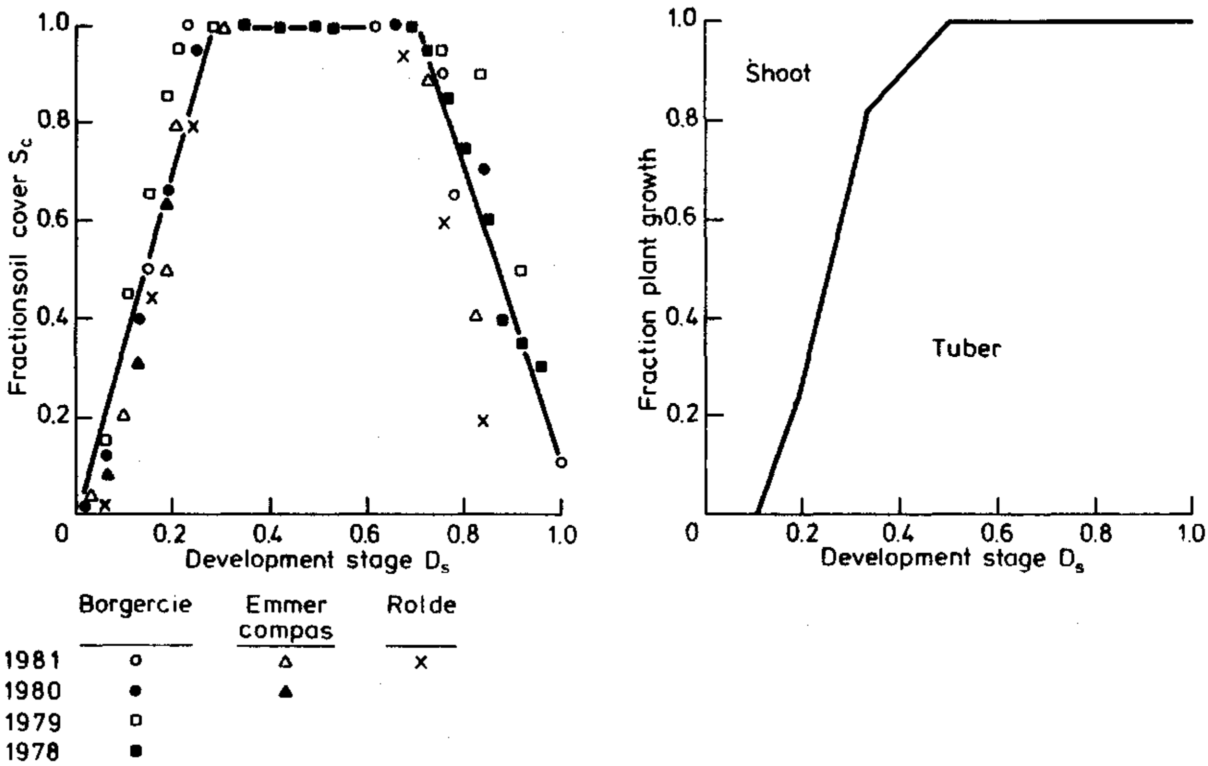


Figure 4 a - Variation of soil cover with development stage for potatoes grown at different places over a number of years

b - Distribution of increase in total dry matter production over shoot and tubers

The hydrological model FEMSATP calculates evaporation from plant and soil, i.e. evapotranspiration. Therefore partitioning of evapotranspiration in transpiration and soil evaporation as a function of leaf area index is required. FEDDES et al ( 1986 ) derived a relationship which is shown in Fig. 5. The relationship has been derived for potatoes and sugar beet. For the derivation it has been assumed that the soil surface is dry. The sum of evaporation from soil, transpiration from plant and evaporation of plant intercepted water is the total loss in water. The total water loss minus the evaporation of plant intercepted water is assumed to be equal to the potential evapotranspiration if one considers a dry surface. Therefore one can write potential evapotranspiration as :

$$E_p = T_p + E_a^{soil}$$

Depending on the development stage, the increase in total dry matter for each time step is distributed over the shoot and tubers ( Fig. 4b ). Having calculated actual growth rate, final dry matter yield of potatoes is obtained by summation of the production per time step from emergence to harvest time. The length of the time step used depends on the output of evapotranspiration rates from the hydrological model FEMSATP.

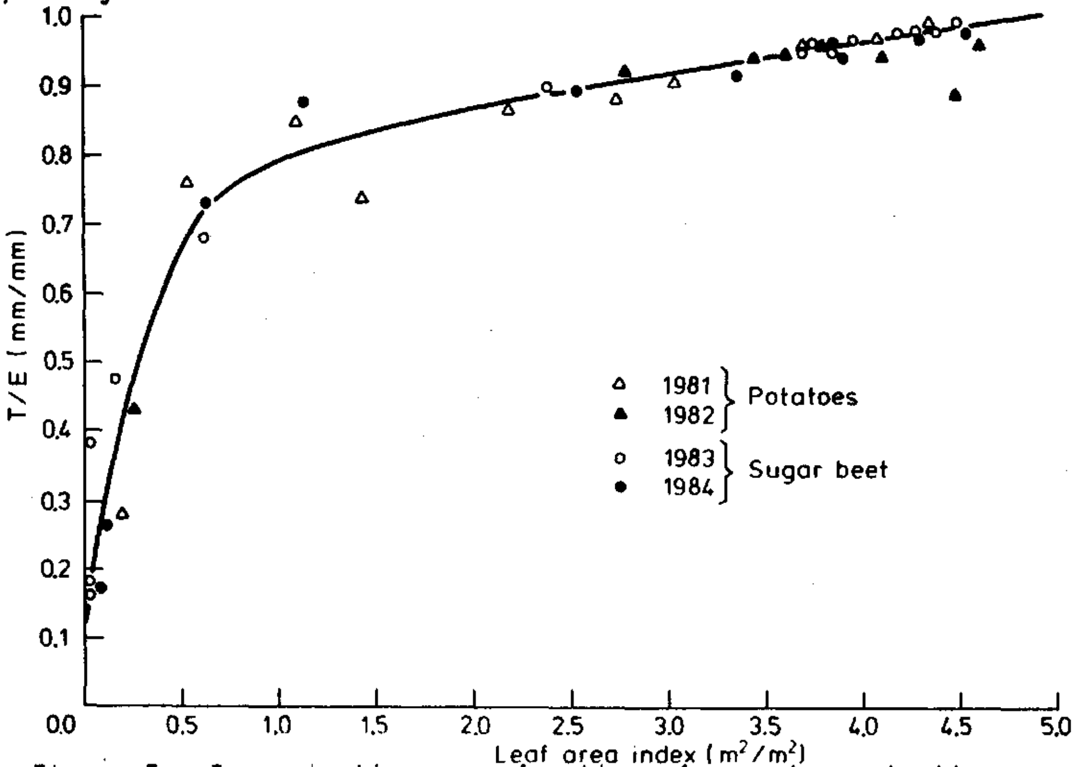


Figure 5 - Transpiration as a fraction of evapotranspiration depending on leaf area index ( FEDDES et al, 1986 )

### 3.3. Yield of other crops

Potato dry matter yield is converted to total fresh yield by means of a factor, for which the value 4.7 is used ( measured dry matter is 21 % of total fresh yield ). Having calculated this actual yield $Q_{act}(p)$ and potential yield $Q_{pot}(p)$ yield of potatoes, the potential yield of other crops j is estimated as :

$$Q_{pot}(j) = F(j) * Q_{pot}(p) \qquad (kg.ha^{-1}.d^{-1}) \qquad (10)$$

where F(j) is the conversion factor to derive the potential production for the crop considered. As an example conversion factor F(j) for various crops applicable for the Southern Peel region are given in Appendix A. Actual fresh yield is calculated as :

$$Q_{act}(j) = \frac{E_a(j)}{E_p(j)} * Q_{pot}(j) \qquad (kg.ha^{-1}.d^{-1}) \qquad (11)$$

where the ratio actual, $E_a$, to potential, $E_p$, evapotranspiration is considered over the period from emergence to harvest time of the crop.

### 3.4. Nutrient application

Having obtained the yield under optimal nutrient supply, one has to correct for the actual nutrient supply, of which nitrogen is the most important. A reduction factor n dependent on the ratio actual to optimal nitrogen supply is introduced ( FEDDES and RIJTEMA, 1983 ) as :

$$n = 1 - a(1-N_a/N_o)^b \quad \text{for} \quad 0 <= N_a/N_o <= 1 \qquad (12)$$

$$n = 1 - c(N_a/N_o-1)^d \quad \text{for} \quad N_a/N_o > 1 \qquad (13)$$

where $N_a$ is the amount of nitrogen applied plus the amount available in the soil and $N_o$ is the demand for optimal crop production. The coefficients a to d are derived from the lines shown in Fig. 6 and given in Table 1.

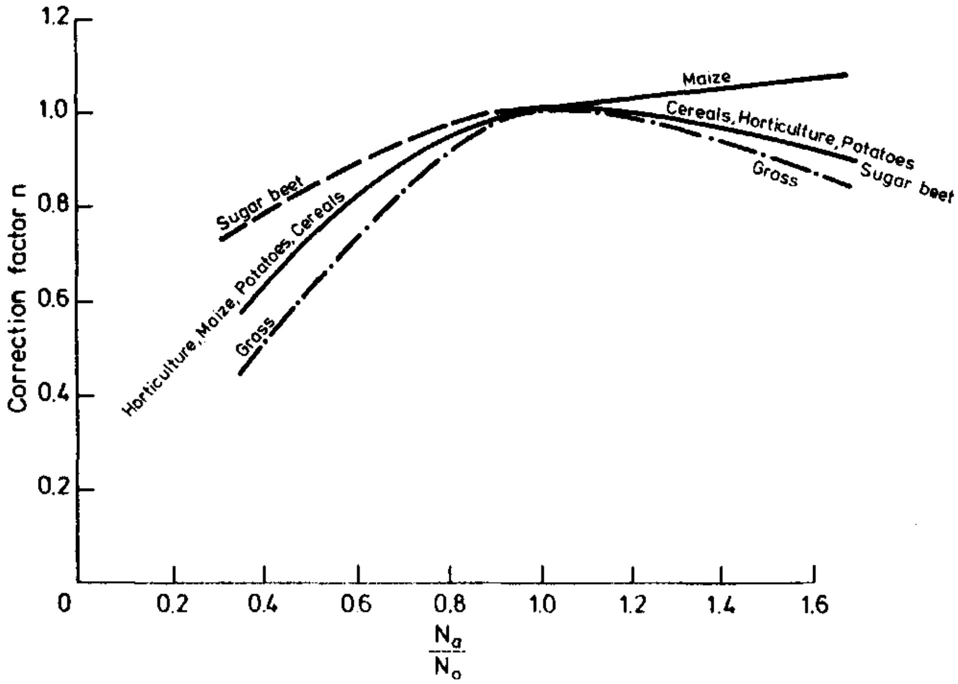


Figure 6 - Reduction in crop production dependent on the amount of nitrogen applied plus that available in the soil

Table 1 - Values of the coefficients used in eqs (12) and (13) for different groups of crops

| crop | a | b | c | d |
|---|---|---|---|---|
| grass | 1.147 | 1.618 | 0.168 | 1.576 |
| cereals, row crops | 0.859 | 1.683 | 0.302 | 1.688 |
| maize | 0.859 | 1.683 | -0.060 | 0.333 |
| horticulture | 0.859 | 1.683 | 0.302 | 1.688 |

Up to now the calculated potential and actual yields should be considered as yields that theoretically can be obtained. One one has to correct these yields for factors other then included in the model. These factors are for instance reduction due to lack of management, occurence of diseases, etc. Hence the actual yield has been multiplied by a 'lumped' factor $\alpha$ ( 0.65 - 0.85 ) to reach at fresh yields that are found in practice.

# 4. INCOME

The income from agricultural crop productions can be determined as :

$$Y(j) = Q_{act}(j) * M(j) - C(j) \qquad (14)$$

where $M(j)$ is the market price and $C(j)$ are all costs related to the production process. Production costs independent of the yield are replacements costs, planting material, fuel, weed control, plant protection, insurances, ect. Costs dependent on the yield are chemical fertiliser, waste application and sprinkling energy costs. The market prices for various crops are listed in Appendix A. Production costs for various technologies in the Southern Peel region were determined by REINDS ( 1985 ).

## 5. EXAMPLES

To demonstrate the use of the models FEMSATP and SIMCROP some water managemment senarios where calculated. First the hydrological model is run for a specific case. Results in the form of evapotranspiration rates and sprinkling quantities are subsequent part of the input data for the agricultural model. The examples discussed in the following paragraphs are performed for the Southern Peel region.

### 5.1. Groundwater extraction

In the Southern Peel region a pumpstation for public water supply is located near Vlierden ( see Fig. 7 of QUERNER and VAN BAKEL, 1984 ). The present capacity of this pumpstation is approximately 10000 $m^3$/d. If the pumping rate is double the present capacity, then the income from agricultural productions for the entire region reduces as shown in Table 2. For the very dry summer of 1976 the reduction in income becomes significant. If we consider the reduction in income over the increased extraction, then every cubic meter of additional extracted water costs dfl 0.11. In these calculations we consider fixed prices per crop and no variation of emergence and harvest time over the years. An optimal nutrient supply is considered as well.

Table 2 - Income from agricultural productions in Southern Peel region for extraction at Vlierden of 10000 $m^3$/d ( present situation ) and 20000 $m^3$/d ( hypothetical situation )

| growing | mln dfl | | weather |
|---|---|---|---|
| season | 10000 $m^3$/d | 20000 $m^3$/d | conditions |
| 1974 | 144.4 | 144.3 | wet |
| 1975 | 143.8 | 143.6 | dry |
| 1976 | 133.6 | 133.2 | very dry |

## 5.2. Sprinkling

The efficiency of sprinkling on a regional level can be judged from calculations with and without sprinkler irrigation. The results of the hydrological model and the crop production and income model are shown in Table 3. The market prices used for the calculations are given in Appendix A. For the production costs the figures as reported by REINDS ( 1985 ) were used. For the replacement cost of sprinkling equipment a figure of dfl 610 /ha has been used and for energy a figure of dfl 0.70 /mm water sprinkled ( cost of labour not included ). The results in Table 3 give a good indication of the effect of sprinkling on a regional level. The results are very much influenced by the technologies present in the Southern Peel region. For some crops the difference in income per hectare is given in Table 4. The typical crops falling under the term small scale and large scale horticulture are given in Appendix A.

Table 3 - Results of calculations from FEMSATP and SIMCROP with and without sprinkling. Nomenclature used : $E_a$, evapotranspiration; $i_s$, sprinkling from surface water; $i_g$, sprinkling from groundwater

FEMSATP

| | no sprinkling | sprinkling | | |
|---|---|---|---|---|
| | $E_a$ (mm) | $E_a$ (mm) | $i_s + i_g$ (mm) | $E_a/(i_s+i_g)$ % |
| 1974 | 421 | 423 | 26 | 8 |
| 1975 | 396 | 408 | 38 | 32 |
| 1976 | 344 | 380 | 81 | 44 |

SIMCROP

| | income in mln dfl | |
|---|---|---|
| | no sprinkling | sprinkling |
| 1974 | 147.9 | 145.1 ( -1.9 % ) |
| 1975 | 143.7 | 142.8 ( -0.6 % ) |
| 1976 | 127.0 | 133.9 ( +5.4 % ) |

Table 4 - Effect of sprinkling on income for some technologies present in the Southern Peel region ( I - no sprinkling; II - sprinkling with capacity as per 1982 )

| | income in dfl/ha | | | |
|---|---|---|---|---|
| technology | 1974 | 1975 | 1976 | |
| small scale hort. | 26010 | 25450 | 22470 | I |
| | 25770 | 25500 | 30420 | II |
| large scale hort. | 2310 | 1570 | 310 | I |
| | 1710 | 1920 | 2370 | II |
| potatoes/sugar beet | 3760 | 3660 | 2160 | I |
| | 3140 | 3330 | 3430 | II |
| maize | 1310 | 990 | 410 | I |
| | 660 | 900 | 870 | II |

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# 7. LIST OF SYMBOLS

| | |
|---|---|
| $A$ | - maximum water use efficiency factor |
| $C$ | - costs related to crop production process |
| $D_s$ | - development stage |
| $E_a$ | - actual evapotranspiration rate |
| $E_p$ | - potential evapotranspiration rate |
| $F$ | - conversion factor between production of potatoes and other crop species |
| $I$ | - leaf area index |
| $M$ | - market price |
| $N_a$ | - amount of nitrogen applied plus available in the soil |
| $N_o$ | - nitrogen demand for optimal crop production |
| $P_{act}$ | - actual photosynthesis rate |
| $P_c$ | - gross photosynthesis rate on clear day |
| $P_o$ | - gross photosynthesis rate on overcast day |
| $P_{st}$ | - gross maximum photosynthesis rate |
| $q_{act}$ | - actual dry matter growth rate per timestep |
| $q_{max}$ | - maximum possible dry matter growth rate per timestep |
| $Q_{act}$ | - actual fresh yield |
| $Q_{pot}$ | - potential fresh yield |
| $Q_t$ | - total potential yield of shoot and tubers |
| $R_c$ | - solar radiation flux |
| $R_s$ | - short wave global radiation flux |
| $S_c$ | - soil cover |
| $t$ | - time |
| $t_e$ | - emergence date |
| $t_h$ | - harvest date |
| $T$ | - temperature |
| $T_a$ | - actual transpiration |
| $T_p$ | - potential transpiration |
| $X_m$ | - maintenance respiration |
| $Y$ | - income |
| $\Delta e$ | - vapour pressure deficit of the air |
| $\frown$ | - fraction of time sky is overcast |
| $\zeta$ | - mathematical parameter |
| $\alpha$ | - 'lumped' factor to convert theoretical yields to yields found in practice |

Appendix A - Conversion factors and market prices

From yields found in practice the conversion factors F(j) used to estimate crop yield from the yield of potatoes are based on information collected by PAGV ( 1984 ). Also the current market prices are from this source. The total ( fresh ) yield, the conversion factor to derive at productions per crop from production of potatoes and the market prices are listed in the table below. The figures are applicable for typical sandy soils in the south western part of The Netherlands - Southern Peel region.

| technology /crop | total yield kg | factor | market price dfl/kg |
|---|---|---|---|
| potatoes | 45000 | 1.00 | 0.15 |
| sugarbeets | 54000 | 1.20 | 0.11 |
| maize | 48000 | 1.07 | 0.06 |
| cereals | | | |
| - barley | 7700 | 0.17 | 0.35 |
| - rye | 8200 | 0.18 | 0.30 |
| small scale hort. | 42650 | 0.94 | 0.83 |
| - leek | 40000 | 0.89 | 0.84 |
| - schozonera | 17000 | 0.38 | 0.48 |
| - pole snap beans | | | |
| - strawberries | 16000 | 0.35 | 2.90 |
| - ridge cucumbers | 65000 | 1.44 | 0.80 |
| - carrots | 65000 | 1.44 | 0.19 |
| large scale hort. | 10840 | 0.24 | 0.61 |
| - garden peas | 4600 | 0.10 | 0.76 |
| - broad beans | 11000 | 0.22 | 0.36 |
| - brussels sprouts | 20000 | 0.44 | 0.90 |
| - witloof chicory | 28000 | 0.62 | 0.30 |
| grassland | | | |
| - dairy cattle | 75000 | 1.66 | 0.07 |
| - rearing cattle | 75000 | 1.66 | 0.07 |

It should be noted that for grassland used for rearing cattle the nutrient supply is in general lower then required for optimal grass production ( e.g. amount of nitrogen applied plus available in the soil is 60 - 80 % of nitrogen demand required for optimal crop production ).

Typical crop growing periods for various crops used for the calculations is given below :

| crop | day no | |
|---|---|---|
| | emergence | harvest |
| small scale hort. | 106 | 305 |
| large scale hort. | 106 | 274 |
| potatoes | 121 | 258 |
| cereals | 80 | 220 |
| maize | 140 | 290 |
| grassland | 60 | 305 |

Appendix B - Typical parameters for potato production

The maximum water use efficiency factor for some years are given below :

| year | A | year | A |
|---|---|---|---|
| 1970 | 3000 | 1976 | 4300 |
| 1971 | 2800 | 1977 | 2100 |
| 1972 | 2000 | 1978 | 2500 |
| 1973 | 3000 | 1979 | 2200 |
| 1974 | 2000 | 1980 | 2800 |
| 1975 | 3300 | 1981 | 2400 |

The production of potatoes is calculated as dry matter. These amounts are converted to total fresh yield with a conversion factor ( dry matter yield is 21 % of total fresh yield ).

For the Southern Peel region the derived conversion between theoretical production and production of the 'average' farmer has been estimated as 0.73.

| | | | |
|---|---|---|---|
| original CROPR model | gross max. photosynthesis of a standard crop leaf area index 5 optimal nutrients and water | $P_{st}$ | |
| | | | actual leaf area index |
| | net photosynthesis of an actual crop | $P_{act}$ | |
| | | | respiration |
| | maximum possible dry matter growth rate (potatoes) | $q_{max}$ | |
| | | | water use efficiency factor<br>actual transpiration<br>vapour pressure deficit |
| | potential/actual dry matter growth rate water limitation | $q_{pot}$    $q_{act}$ | |
| | | | distribution over shoot and tubers<br>summation over time steps<br>conversion to fresh yield |
| | fresh yield (potatoes) | $Q_{pot}$    $Q_{act}$ | |
| | | | conversion to other crops |
| | potential fresh yield crop j | $Q_{pot}(j)$ | |
| | | | reduction - water limitation crop j ($E_a/E_p$) |
| | actual fresh yield crop j | $Q_{act}(j)$ | |
| | | | nutrient limitation crop j |
| | nutrient reduced fresh yield crop j | $Q^N_{act}(j)$ | |
| | | | reduction - lack of management, diseases, etc. |
| | average fresh yield found in practice | $\alpha Q^N_{act}(j)$ | |