Int. Agrophysics, 1996, 10, 269-276

THE MODEL CORNWAY - A TOOL FOR ANALYSING THE RELATION BETWEEN SOIL-WATER REGIME AND THE YIELD OF MAIZE (*ZEA MAYS* L.)

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Abstract. Submodels for simulation of the effect of soil water regime (GLOBAL) and grain yield of maize (*Zea Mays*, L.) CORNY can be modified and then used simultaneously as a model CORNWAY to estimate relative plant yields. The first model (GLOBAL) is a mathematical deterministic model which simulates water transport in a soil profile during the vegetation period of crops. Model CORNY is semiempirical model for calculating the continuous reduction of the potential yield of maize crop due to soil water deficit during the vegetation period. The most important factor, among others, is the water suply of canopy. Version of CORNY submodel as used here is focused on the role of water in yield reduction. It is supposed that other factors did not limit this process.

Keywords: simulation model, grain yield of maize, stress factor, stress-day index, planting date delay

INTRODUCTION

The effects of water regime of soils on corn yields

In general the purpose of agricultural water management is to increase the efficiency and reliability of plant production. The goal is consistent with high yields at minimum investment of water, energy and other resources. That means, plants should be protected from dry and wet stresses, i.e., soil water potential is kept within certain limits out of anaerobic and dry conditions, respectively. Drought, and lack of soil aeration can cause a decrease in plant production. Mainly in humid regions, artificial drainage systems are installed to satisfy two specific requirements:

1) To insure trafficable conditions for seed bed preparation, planting, harvesting and other field operations.
2) To remove excessive soil water from the root zone during high rainfall periods so that crop yields are not reduced by oxygen deficiences or other stresses caused by wet soils.

The stress degree also varies from season to season, depending upon weather conditions. To avoid a drought situation, it is necessary to irrigate the soil, according to plant demand. The degree of crop stress that occurs due to the deficient and/or excess soil water depends upon the plant growth during which stress occurs [19].

Used models

The mathematical simulation model GLOBAL was developed at the Institute of Hydrology SAS by Majerčák and Novák [9]. It is used as a tool to study water transport in soil under isothermal conditions. Model GLOBAL is to calculate the distribution of water and soil water potentials with respect to time, depending on the initial and boundary conditions. It is assumed that water transport takes place predominantly in a vertical direction, horizontal water flows are not considered. It is also assumed that the influence of concentration distribution of dissolved substances upon water transport is negligible.

The basis of the model is a numerical solution of a nonlinear partial diferential equation for the transport of water in a vertical direction. When solving this equation, the influence of hysteresis of retention curve is considered. The numerical solution in the GLOBAL model is based on the use of Galerkin's modification of the finite element method. A modified version of the numerical solution of Richards equation is used, as it is given by van Genuchten [16].

The boundary condition on the soil surface is given by the mean rate of precipitation reduced by the interception of canopy, and by the intensity of evaporation. In the days without any precipitation, the rate of water transport from soil surface to the atmosphere is equal to evaporation intensity. Transpiration rate is equal to the rate of water uptake by roots. The lower boundary condition is defined by the mean values of soil potential, or by the vertical rates of water flow in the corresponding depth under the soil surface. The ground water flow is not the subject of simulation in the GLOBAL model.

The basic precondition for the success of the simulation model for water transport is the correct determination of evapotranspiration rates and their structure which enter the model as a boundary condition. In the GLOBAL model the method of evapotranspiration calculation proposed by Novák [10] is used. A significant advantage of this method is the possibility of determinating the velocity coefficient of the turbulent transport of water vapour from an evaporating surface to the atmosphere.

The submodel CORNY is able, in cooperation with submodel GLOBAL and model CORNWAY to quantify water stresses in maize (*Zea mays* L.) caused by both excessive and deficient water conditions and to weigh those stresses according to the stage of growing season and crop susceptibility at the time they occur. The method is added to predict the yield reduction due to planting delay. Submodel CORNY was implemented to the model GLOBAL using its capability of computating water content distribution in soil profiles and daily values for actual transpiration. Thus, we can obtain the daily values of the stress-day index for wet conditions and the ratio of potential to actual transpiration to compute the drought stress.

In general, the model CORNWAY, composed of submodels CORNY and GLOBAL, is able to give information about the possible development of maize yield affected by changing climatological conditions.

GENERAL CROP RESPONSE MODEL

The general crop response model used may be written as showed Skaggs *et al.* [13] as:

$$Y_r = Y_{rw} \, Y_{rd} \, Y_{rp} \tag{1}$$

where Y_r is the relative yield, $Y_r = Y / Y_o$, $Y_{rw} = Y_w / Y_o$, $Y_{rp} = Y_p / Y_o$. Y is the yield for a given year, Y_o is the potential yield that would be obtained in the absence of soil water stress conditions including no delay in planting date, Y_w is the yield that would be obtained if only wet stresses occur, Y_d is the yield that would be obtained if only drought stresses occur and Y_p is the yield that would be obtained if the reduction is only due to a delay in planting date.

The crop response models can be divided into two groups:

- generally oriented, in which plant production is estimated using formulas for intensity of photosynthesis of particular plants, and then reducing it to actual yields using the correction factors;
- semiempirically oriented models, directed to particular plant species. Submodel CORNY as a part of CORNWAY model belongs to these kind of models.

CROP STRESS FACTORS

Stress-day index concept

The above mentioned crop response model is based on the stress-day index (SDI) concept proposed by Hiler [6]. It assumes that the effect on yields due to the stresses caused by excessive or deficient soil water conditions depend on crop growth stage. The SDI is determined by multiplying a crop susceptibility factor and a stress-day factor. Then the product is summed for all stages of growth:

$$SDI = \sum_{i=1}^{N} CS_i \, SD_i \qquad (2)$$

where SDI is the stress-day index, CS_i is the crop susceptibility factor, SD_i is the stress-day factor and N is the number of growth stages considered.

Stress factor caused by wet soil

An objective function for the stress factor caused by wet soil conditions was proposed by Bouwer [1] as:

$$SEW_{30} = \int_0^T f(x)dt \qquad (3)$$

where t - time during the growing season (days), T - lenght of the growing season (days), x - depth of the water table from the surface (cm).
Function $f(x)$ is defined as $f(x) = 30 - x$ for $x<30$ and $f(x) = 0$ for $x>30$.

As suggested by Ravelo [11], crop response wet soil conditions is related to a stress-day index for wet soil conditions - *SDIW*. Daily SEW_{30} values were taken as the stress-day factor and the SDIW was calculated as:

$$SDIW = \sum_{j=1}^{N} CS_{wj} \, SEW_{30j} \qquad (4)$$

where CS_{wj} is the daily crop susceptibility and N is the number of days in the growing season. Crop susceptibility factors for three growth stages of corn for a wide range of climatic conditions and corn varietes are well known. They are presented in Table 1 presented by Skaggs *et al.* [13].

Table 1. Crop (corn) susceptibility factors CS_w for excessive soil water conditions

Growth stage	Days after planting	CS_w
I	0 - 42	0.51
II	43 - 80	0.33
III	81 - 120	0.02

Stress factor caused by deficient soil water conditions

The stress-day index concept was again used to predict the effect of deficient soil water conditions on crop response. The methods used for this component of the model were proposed by Sudar *et al.* [15]. The stress-day factor (Sudar's water stress index) was taken as 1-*AT*/*PT*, where *AT* is the daily actual transpiration total and *PT* is the daily potential transpiration total. The stress-day index for drought stress, *SDID* (stress day index for dry soil conditions) may then be calculated by the equation:

$$SDID = \sum_{j=1}^{N} CS_{dj}(1 - AT_j / PT_j) \qquad (5)$$

where CS_{dj} is the daily crop susceptibility factor for drought stresses and the subscript j indicates the day. N is the number of days in the growing season.

Sudar *et al.* [15] developed crop susceptibility factors for drought stress using literature data from several sources. Based on his results, the following equations were used to determine the crop susceptibility factor for drought stress in corn:

$$CS_{dj} = 0 \quad \text{for} \quad j \le 26 \qquad (6)$$

and

$$CS_{dj} = -1.17 + 0.058j - 0.0005j^2 \quad \text{for } j>26. \qquad (7)$$

Relative yield in the case of excessive soil water conditions

A relationship between relative yield of corn and *SDIW* (stress day index for wet soil conditions) was developed on the base of field experiments realised by Schwab *et al.* [14], Ritter and Beer [12], Chaudhary *et al.* [2], Joshi and Dastane [7]. The complete analysis of all these data was presented by Hardjoamidjojo [5]. The relationships used by the above mentioned author for corn are as follows:

$$Y_{rw} = 1.0 \quad \text{for } SDIW \leq 8.0 \tag{8}$$

$$Y_{rw} = 1.03 - 0.0042\, SDIW \quad \text{for } 8.0 \leq 245 \tag{9}$$

$$Y_{rw} = 0.0 \quad \text{for } SDIW > 245 \tag{10}$$

In general, relationships like Eqs(8), (9) and (10) can be estimated even for different plants, but further field data are needed.

Relative yield in the case of deficient soil water conditions

The relationship between relative yield and *SDID* as calculated from Eq.(5) is expressed by Sudar *et al.* [15] as the following linear function of *SDID*:

$$Y_{rd} = 1.0 - 0.112\, SDID. \tag{11}$$

Effect of planting date delay on yields of corn

Corn yields are significantly reduced even if the planting date is delayed beyond an optimum period. The results of field tests were presented by Krenzer and Fike [8]. The estimating the effect of delay in planting on yields it was assumed that the observed effects were due to such factors as temperature and day length, and not to deficient or excessive soil water conditions, which are considered in the other components of Eq.(1). In the model CORNWAY the following relationships are used to estimate the effect of planting date delay on relative yield:

$$Y_{rp} = 1.0 - 0.0087\, PD \quad \text{for } PD < 42 \tag{12}$$

$$Y_{rp} = 1.33 - 0.0166\, PD \quad \text{for } 42 < PD \leq 80 \tag{13}$$

$$Y_{rp} = 0 \quad \text{for } PD > 80$$

where *PD* is the plant date delay (days).

SUBMODEL CORNY

The submodel CORNY is based on the theory, presented above. It was implemented in the model of soil water regime GLOBAL, using its capability for precise computation of water-content distribution in soil profile and of daily values of actual transpiration. Thus, we can obtain the daily values of SEW_{30} to compute the stress-day index for wet conditions and the ratio *AT/PT* to compute drought stress. The value of planting date delay is entered to calculate the reduction of yield due to this stress factor. In the output of model CORNWAY Y are values of relative yield (given by Eq.(1)) and its components, given by Eqs(2)-(14), as they can be expected at given day.

COMPARISON OF REAL AND COMPUTED YIELDS

The calculation of potential grain yield (Y_{pg}) was carried out independently by two methods for a top yield locally adapted genotype of maize grown in western Slovakia, Trnava (48°23'N. lat., 17°35' E. ln., 146 m a.s.l.). The soil was loamy chernozem on loess.

The production process was not limited by nutrients, diseases, pests, growing technology and weed infestation.

The first method estimates potential yield Y_{pg} using as the inputs incoming photosynthetically active radiation ($PhAR_{inc}$) for time interval since emergence to physiological ripeness (65 % of grain dry matter), 5 % of *PhAR* effectiveness in dry matter production (ε_{inc}). Other input data are: energy equivalent of dry matter Q_{dm} = 17 GJ t^{-1} and maximum grain harvest index (HI_{max}) estimated for given conditions and genotype ($HI_{max} = 0.55$).

$$Y_{pg} = \frac{PhAR_{inc}\, \varepsilon_{inc}}{Q_{dm}} HI_{\max} \tag{15}$$

where Y_{pg1} - potential grain dry matter yield (t ha^{-1}), $PhAR_{inc}$ - sum of incoming photosynthetically active radiation (λ = 400-700 nm) in period emergence - physiological ripeness of grain (GJ ha^{-1}), ε_{inc} - coefficient of utilization of $PhAR_{inc}$ in biological (dry matter) yield formation, Q_{dm} - energy content of dry matter (GJ t^{-1}), Qdm = 17 GJ t^{-1}, HI_{max} - maximum grain harvest index.

The calculation for the year 1981 is:

$$Y_{pgl} = \frac{12046 \cdot 0.05}{17} 0.55 = 19.49 \ \text{t ha}^{-1} \tag{16}$$

The calculated value of Y_{pg} by the first method for the year 1981 is Y_{pg1} = 19.49 t ha^{-1}. The field estimated yield of grain dry matter in the year 1981 was Y_{rg} = 5.60 t ha^{-1} and the ratio Y_{rg}/Y_{pg1} = 5.60/19.49 = 0.287. The values used in the Eq.(1) were based on data pub-lis-hed by Vidovič [17,19].

The second method used is the Wageningen method by de Wit [3] described in the paper Doorenbos *et al.* [4]. Modified equation to calculate maximum grain matter yield was given by Vidovič (unpublished) :

$$Y_{mg}=\frac{K\,cH\,cT\,G\,Y_0}{1000} \tag{17}$$

$$Y_0=F\,y_0+(1-F)\,y_c \tag{18}$$

$$F=\frac{(R_{se}-0.5\,R_s)}{0.8\,R_{se}} \tag{19}$$

where Y_{mg} - maximum grain dry matter yield (t ha^{-1}), K - correction coefficient for crop species, cH - correction coefficient for harvested part, cT - correction coefficient for temperature, G - growing period length (day), Y_0 - gross dry matter production of a standard crop per day (kg ha^{-1} d^{-1}), F - fraction of the daytime radiation, y_0 - gross dry matter production rate of a standard crop for an overcast day (kg ha^{-1} d^{-1}), y_c - gross dry matter production rate of a standard crop for a clear day (kg ha^{-1} d^{-1}), R_{se} - maximum active incoming shortwave radiation on clear days (cal cm^{-2} d^{-1}), Rs - actual measured incoming shortwave radiation (cal cm^{-2} d^{-1}).

The calculation for corn yield in the year 1981 is:

$$F=\frac{400-0.5\cdot 529}{0.8\cdot 400}=0.42 \tag{20}$$

$$Y_0=0.42\cdot 256+(1-0.42)485= \\ 389\ \text{kg ha}^{-1}\ \text{d}^{-1} \tag{21}$$

$$Y_{pg}=Y_{mg}=\frac{1.9\cdot 0.55\cdot 0.41\cdot 114.389}{1000}= \\ 19.0\ \text{t ha}^{-1}. \tag{22}$$

The ratio of real (Y_{rg}) and potential grain yield calculated by this method (Y_{pg2}) for 1981 was 5.60/19.00=0.29.

The calculation of potential grain yield by the 1st method (Y_{pg1}) for 1982 is:

$$Y_{pg1}=\frac{12221\cdot 0.05}{17}0.55=19.77\ \text{t ha}^{-1}. \tag{23}$$

The calculation of potential grain yield by the 2nd method (Y_{pg2}) for 1982 is:

$$F=\frac{400-0.5\cdot 523.9}{0.8\cdot 400}=0.43 \tag{24}$$

$$Y_0=0.43\cdot 256+(1-0.43)\cdot 485= \\ 386.5\ \text{kg ha}^{-1}\ \text{d}^{-1} \tag{25}$$

$$Y_{pg}=Y_{mg}=\frac{1.9\cdot 0.55\cdot 0.48\cdot 119\cdot 386.5}{1000}= \\ 23.07\ \text{t ha}^{-1}. \tag{26}$$

The ratios of real/potential grain yield for 1982 by the 1st and 2nd method were:

$$Y_{rg}\,/\,Y_{pg1}=8.32/19.77=0.42 \tag{27}$$

and

$$Y_{rg}\,/\,Y_{pg2}=8.32/23.07=0.36, \tag{28}$$

respectively.

RESULTS

The computed relative yield development during the vegetation period of maize grain Yr using the CORNWAY model are in Figs 1 and 2. Simultaneously daily air temperature T and precipitation P for two seasons are shown. The advantage of the presented approach is the possibility of estimating current the potential yields, not only final values as is typical for current models.

To validate this model potential, yields were simulated during ontogenesis based on field data measured in 1981 for conditions of south-western Slovakia (location Trnava, 48° 23'N lat, 17°35'E long, 146 m. a.s.l.). Soil was silty chernozem on loess, ground water table did not influence soil-root zone. The value

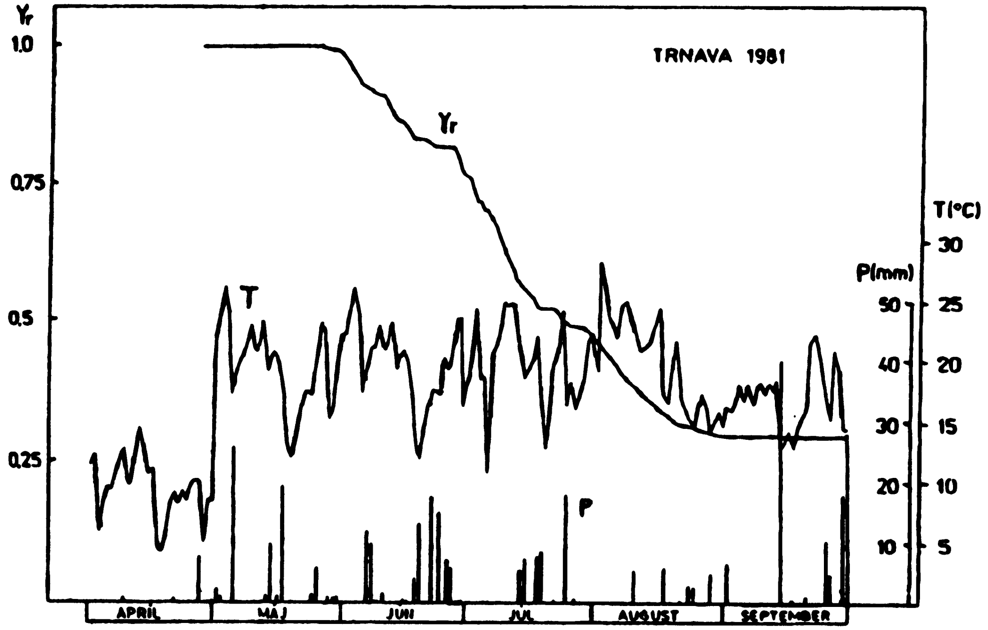

Fig. 1. Relative yield of maize grain (Y_r) during the vegetative period of 1981. Trnava, South Slovakia, Haplic chernozem.

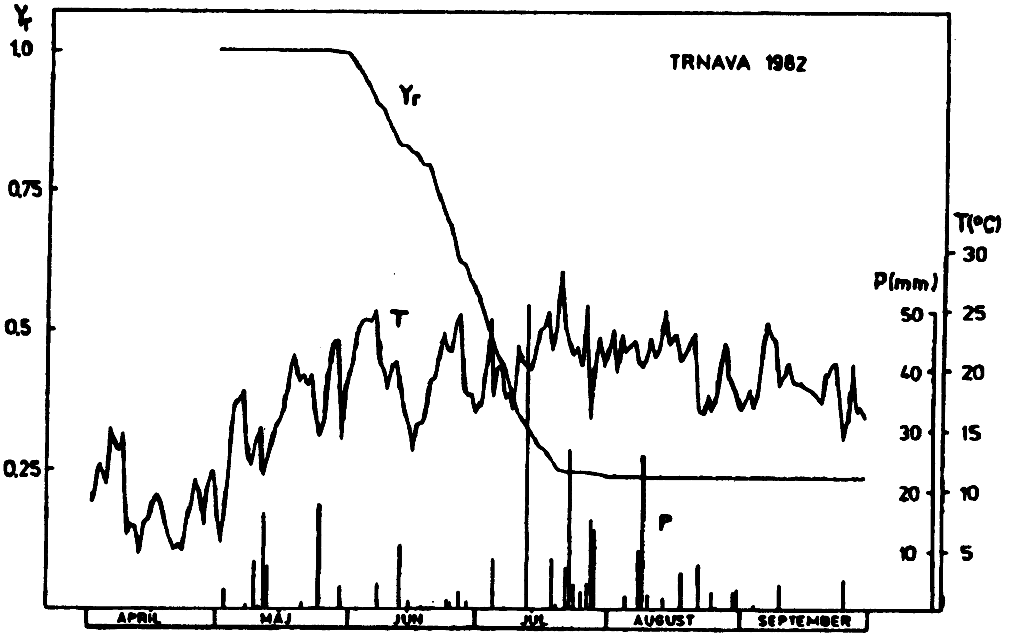

Fig. 2. Relative yield of maize grain (Y_r) during the vegetative period of 1982. Trnava, South Slovakia, Haplic chernozem.

of simulated relative yield of maize (i.e., ratio of real to potential yield) was 0.29 in physiological ripeness. To verify the model, potential grain dry matter was calculated by two independent methods. The first one was a conventional method based on the effectiveness of the incoming photosynthetic active radiation in grain dry matter yield formation. The second was our modification (Vidovič) [18] of 'Wageningen' method based on the de Wit [3] conception and described by Dorenboos *et al.* [4]. The values of potential grain dry matter yield calculated by the first, respectively by the second method were 19.49 t ha^{-1}, and 19.00 t ha^{-1}, values of the real and calculated potential grain dry matter yields ratios were 5.60/19.49 = 0.287 and 5.60/19.00 = 0.295, respectively. The value of simulated relative yield for the year 1981 was 0.290.

For the year 1982 the value of simulated relative yield was 0.2394 and the ratios of real and calculated potential grain dry matter yields ratios were 0.42 and 0.35, respectively.

CONCLUSIONS

The model CORNWAY for the simulation of the effect of soil water regime on the yield of maize grain (*Zea Mays* L.) was developed. The model is a combination of two models - GLOBAL and CORNY. The first model (GLOBAL) is a mathematical deterministic model which simulates water transport in a soil profile during the vegetation period of crops. Model CORNY is a semiempirical model for calculating the continuous reduction of potential yield of maize crop due to soil water deficit during the vegetation period. The most important factor among others is the water supply of canopy. The version of the CORNY model as used here is focused on the role of water in yield reduction. It is supposed that other factors did not limit this process.

The model GLOBAL is able to predict (and to analyse) water dynamics in layered porous media, composed from five layers with different hydrophysical characteristics. An original method of estimating evapotranspiration and its structure, soil water extraction by roots and was applied in GLOBAL. The model CORNY was implemented in model GLOBAL using its capability of precise computation of water content distribution in soil profile and of daily values of actual transpiration.

The results of simulated and independently calculated values of real to potential crop yields ratios (i.e., relative yields) are surprisingly close for 1981. For 1982 the coincidence of the simulated and determined relative grain dry matter yields was not so close as in 1981. The simulated relative grain dry matter yield was 57 and 67 % of the determined relative yield by the first and second method, respectively. So we have the possibility to predict, on a day-by-day basis, the answer of crop (maize) on the soil water conditions and weather factors.

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