Test of the Biological Module of CERES-Maize Model in Lysimeters on Chromic Luvisols

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Abstract

This paper reports on CERES-maize model stepwise calibration, modification and validation using independent data from specific experiments carried out in a chromic luvisol (Chelopechene), Sofia field,1997-1999. Laboratory based water conductivity curve *WCC* (eq.1) and water retention curve *WRC* (eq.2) are calibrated (step **i**) and adjusted to data measured in field (step **ii**) (Fig.1; Table 3). Field observations of water dynamics under maize *hybrid Kn 509* relative to optimal nitrogen supply **N200** (kg ha^{-1}) and variable water stress (irrigated **A1** plots/lysimeters №1 and №2) are used to modify the function of Root Water Absorption (eq.3) (step **iii**). The ability of calibrated biological module of CERES-NC-Maize model to make predictions without any further adjustments of parameters is tested against independent three-year dataset (1997-1999) collected in the same field (Chelopechene) but in lysimeter №1 (step **iv**). Observed water contents in the 1.30 m root zone ***PESW*** and soil layers ***SW*** (Figs.3a, 3b, 3c, 3d), actual crop water uptake (evapotranspiration ***ET***) (Figs. 4 and 5) and water fluxes prove acceptable agreement with validated model outputs. Model predictions of crop growth and dry weights of maize are acceptably precise in most of the tested situations (Fig.6). The results support the use of tested CERES-NC model in prediction of aboveground dry matter, water balance and storage under maize on Chromic Luvisols in Sofia field.

Key words: “crop-soil-atmosphere” system, transport of water, lysimeters’ experiments; CERES-NC-maize model parameterisation, model predictive capacity

Introduction

Evaluation of environmental impacts and consequences of hydrological events requires estimation of different fluxes of water and pollutants, associated with agricultural practice and pedoclimate data, within the “soil-plant” system and at its boundaries. Such variables, as crop evapotranspiration, fluxes of water and nitrogen below the root zone, yield etc, are estimated by balance of water and nitrogen in the system. Model use in a predictive mode is indispensable in such analyses. Numerous models, dealing with the risk of pollution and consequences of hydrological extremes in agriculture, have been developed for the last twenty years. They treat the ensemble of processes in the cycle of water and nitrogen of the soil-crop system. In the general structure of such models three basic modules usually describe the following phenomena:

-physique: transport of water, solutes etc. in the soil and its interface with the atmosphere,

-microbiological: degradation of the organic matter in the soil, nitrification, de-nitrification,

-biological: growth and development of plants related to their functioning in the soil by the module of root uptake.

Different level of details is possible in each module. Predictive capacity and parameterisation feasibility of the modified CERES-maize model (Jones & Kiniry 1986; Gabrielle et al.1995; Gabrielle et al.1996) have been tested with Bulgarian pedoclimate and crop data within the framework of an INCO-COPERNICUS project (Forth framework Program of EC) on evaluation of risks and monitoring nitrogen and pesticides fluxes at the crop level on the Romanian and Bulgarian plain. Soil and crop model parameters were calibrated on a Chromic Luvisol (Chelopechene field, Sofia region) on the basis of data collected under optimal nitrogen dressing from dry lands, optimally irrigated plots and lysimeter №2 in 1997 (Final Project Report of IC15CT96-0101; Popova et al., 1999; Popova and Kercheva, 2005). Modelling the dynamic of water and nitrogen uptake by plant plays a critical role since it intervenes in the principle terms of water and nitrogen balance in the soil-crop system. The objective of this report was to improve and validate CERES-maize model predictions about water disposal in the soil and biological response to it for the situation under study. For that purpose the functions of root water absorption-RWA and crop growth (Jones & Kiniry 1986) were tuned under maize. Validation data were collected from similar situations in the same field but in a different lysimeter (№1) in 1997 and following 1998 and 1999. The biological module was validated over three years by comparing the model output to observed lysimeter data, which were not used in model calibration so far, as crop evapotranspiration, soil water disposal and dry matter content in above ground plant and ears.

Materials and Methods

Environment of models' test

Modified CERES-maize model (Jones & Kiniry 1986; Gabrielle et al.1995; Gabrielle et al.1996) was tested at the experimental site of Chelopechene in the region of Sofia. The soil is a moderately permeable Chromic Luvisol (Table 1).

The region of Sofia belongs to the European moderate-continental zone. Mean air temperature in the coldest month January is -2.4^{o}C, and it is 20.2^{o}C in the hottest one July. Annual precipitation sum is 636 mm on the average. The precipitation totals during maize vegetation periods-Pr (Table 2) are not enough to satisfy potential crop water use and in most of the years irrigation requirements (I) vary from 60 to 276mm.

Table 1. *Soil texture and laboratory based saturated hydraulic conductivity ($K_{sat-lab}$), Chelopechene field.*

Depth, cm	Soil texture classification	Soil particles, %			$K_{sat-lab}$
		Clay <0,002 mm	Silt 0,002-0,05 mm	Sand 0,05-2,00 mm	cm/day
0-28	clay loam	32	32	36	93,30
33-45	clay	43	27	30	15,90
61-71	clay	42	25	33	20,20
95-130	Sandy clay loam	24	15	61	39.90

Vegetation seasons of model test (1997, 1998 and 1999) covered a wide range of input water balance components- I and Pr (table2) and probability of exceedance of precipitation P (28%<P<67%).

Table 2. *Precipitation totals (Pr, mm), probability of exceedance of precipitation (P, %) and irrigation depths (I, mm) in Chelopechene field during different maize vegetation periods.*

Vegetation Period	Years of extremes				Years of model test					
	P=10% (Wet)		P=90% (Dry)		1998,P=59% (Average)		1997, P=67% (Moderately dry)		1999,P=28% (Moderately wet)	
	Pr, mm	I, mm	Pr, mm	I, mm	Pr, mm	I, mm	Pr, mm	I, mm	Pr, mm	I, mm
1.05-30.09	380	61[1]	180	276[1]	277	160[1]	263	183[1] 132[2]	349	160[1] 120[2]

1) Required irrigation depths for water application scheduled at 85% of FC (according CROPWAT programme, Smith, 1991)

2) Real irrigation depths in lysimeter №1.

Three-year meteorological data (air temperature, precipitation, wind velocity, air humidity and global sun radiation) monitored on a daily basis in MTO field station of N. Poushkarov Institute of Soil Science (1997-1999) were used in these analyses.

Descriptions of the model and its modifications

CERES model (Jones & Kiniry 1986) is composed of different sub-models, each one functioning independently with its own input/output, and using atmosphere/plant/soil parameters. Redistribution of precipitation/irrigation input, values of drainage, potential evapotranspiration, actual soil evaporation and plant transpiration are calculated in the soil water balance subroutine. Following an infiltration a layer can hold the amount of water corresponding to the difference between current volumetric water content and saturation (**SAT**). If the new soil water storage is more then Drain Upper Limit (**DUL**) the excess of water above DUL drains by unsaturated flow from the layer and the potential infiltration in the next layer is set. The total flow out of the lowest layer of the soil profile presents deep percolation. Water Flow Sub-model is taken from Gabrielle et al. (1995) who has implemented a semi-empirical Darcy's low for water movement in the soil profile in saturated and unsaturated conditions. He uses the following equations of **WCC** (water conductivity curve):

$K(\theta)$=Ksat.exp [A(θ-θsat)] (1)

and water retention curve –**WRC** (Driessen, 1986):

$$\varphi(\Theta) = \exp\sqrt{\frac{\log\frac{\Theta_{sat}}{\Theta}}{\gamma}} \quad (2)$$

, where $K(\theta)$ and K_{sat} (cm day^{-1}) are the hydraulic conductivity respectively at θ and θ_{sat} water contents, θ_{sat} (cm^3 cm^{-3}) is volumetric water content at saturation, parameter A (unitless) depends on soil texture and hydrologic classes, $\varphi(\theta)$ (cm water) is the matrix suction, parameter γ (cm^{-2}) is a texture related constant that accounts for the soil suction curve. Soil water balance subroutine also calculates potential and actual evaporation and transpiration by the model of Ritchie (1972). Upward and downward unsaturated flows between the Lower Limit (LL) and DUL are thus calculated (Jones & Kiniry 1986).In the model (Jones & Kiniry 1986) the process of crop uptake in the soil is interpreted in terms of crop demands and soil disposal. The flux of root water absorption J_w (m water day^{-1}m^{-1} root) is calculated for a layer of soil of thickness Z (m) by the following equation:

$$J_w = 2.67 * 10^{-5} \frac{\exp\left[62\left(\theta - \theta_{pf}\right)\right]}{6.68 - \ln(RLV)} Z \quad (3)$$

, where θ is average volumetric water content in the day, θ_{pf} is wilting point. RLV is root length density (m root m^3 soil). This function reflects the disposition of water in the soil as well as the capacity of the root system to extract its elements. The crop model of CERES-maize is consisted of three modules of crop growth: phenological one, module of photosynthesis and module of restraints. The last one confronts the demands of the plants with the soil disposal and then penalises the functions of crop growth and elongation under limiting conditions.

CERES-maize model (Jones & Kiniry 1986; Gabrielle et al.1995) was purposely modified in this study. The simulation of preferential fluxes and thus soil nitrogen fate was improved by introduction of special looping in the model code which redistributed immediately the excess of input water above SAT in the top soil layer by saturating consistently the lower layers in the manner of cascade.

Model calibration and validation specifics

Model test on a Chromic Luvisol has been in process since 1997 according to the following methodology: (i) deriving a first set of soil and crop development model parameters for the water balance sub-model; (ii) adjustment of laboratory WRC (eq.2) to water retention data measured in field; (iii) using these optimised parameters for calibrating the remaining biological parameters of crop growth and root water absorption (RWA-eq.3); and (iv) adjustment of soil and crop parameters for variable nitrogen treatments. Field data obtained from the experiments with optimal nitrogen dressing and variable water stress were used for steps (i), (ii) and (iii). These steps were initially made of data collected from dry lands, optimally irrigated plots and lysimeter №2 in 1997, when maize vegetation season was moderately dry (Final Project Report of IC15CT96-0101; Popova, 2008; Popova et al., 1999, Popova 2000). The calibration of water balance sub-model (step i and step ii) used to be performed on a part of the data set (from irrigated and non-irrigated plots) while the other part from lysimeter №2 (the "split sample method") were used to validate step (i) and step (ii) and then to start calibration step (iii) by testing and modifying, if needed, the functions of RWA (eq.3) and crop growth. Model modification in order to predict better preferential fluxes and redistribution of precipitation and irrigation water input in the soil was also checked. The ability of calibrated and modified model to make predictions without any further adjustments of parameters was tested in this study against independent three-year data (1997, 1998, 1999) collected in the same field but from lysimeter №1 during project and post-project field campaign (extrapolation test). These data were not used in the calibration exercise so far. Soil moisture for model validation was assessed by tensiometers (Hillel, 1980) and TDR (Guidelines for TRIME application, Fundinger et al., 1995). For this purposes the lysimeter №1 was instrumented with mercury tensiometers at the depth 40, 70, 100 and 130cm (since June 1997) and fibber-glass probe access tubes installed till 2m (since 1998). Data about actual maize evapotranspiration-ET in the lysimeter were obtained by water balance and justified with independent ET calculations (Delibaltov, 1972; Zahariev et al.1986) in a companion paper presented in a conference. Model input of reference surface evaporation for the years of model test was calculated for alfalfa on the bases of daily climate records. Dry weights of the crop components were evaluated by destructive sampling of 2-4 plants over vegetation and 70-100 plants at harvest. All these data were extensively used for validation by comparing them to model output. Such procedure was adopted to make sure that finally the parameters of physical water transport in the soil and at the boundaries of the soil-crop system and biological extraction of the roots were representative for the field. The goodness of model predictions was evaluated by graphical methods. Graphical model test included comparison between simulated and measured soil moisture content and potentially extractable soil water-PESW in the root zone, maize evapotranspiration and dry matter weights of above ground crop and ears (grains +cobs + leaf sheets) in one and the same lysimeter №1 over the period from 1.05.1997 to 1.10.1999.

Results and Discussion

Results were presented following the stepwise procedure of CERES-maize model test

Improvements of predictions of water disposal in the soil

Water retention curve (eq.2) of CERES-maize was fit to laboratory based data (Koleva, 1973 ; Kalcheva 1991) in calibration step (i) as shown in Fig.1-a and then adjusted in Fig 1-b to field tensiometers reading (step ii). As a result of calibration step (ii) θ_{sat} (eq.2) was adjusted to field conditions by regressing tensiometers' data points under the constraint to keep γ-slope parameter at the laboratory-based value (dashed line in Fig.1-b). Step (ii) proved that "laboratory WRC"(full line in Fig.1-b) overestimated water content by 0.07-0.12 cm^3/cm^3 on the Chromic Luvisol. Soil water parameters derived after step (i) and step (ii) of model calibration were listed in Table 3.

CERES-maize (Jones & Kiniry 1986; Gabrielle et al.1995) calibration exercises on multilayered Chromic Luvisol (table 1) showed that after intensive water supply, due to the daily step of model simulations, the withdrawal of the excess of water above field capacity from the top layer took much more time (several days) then the real water redistribution time in reality (Fig.2).

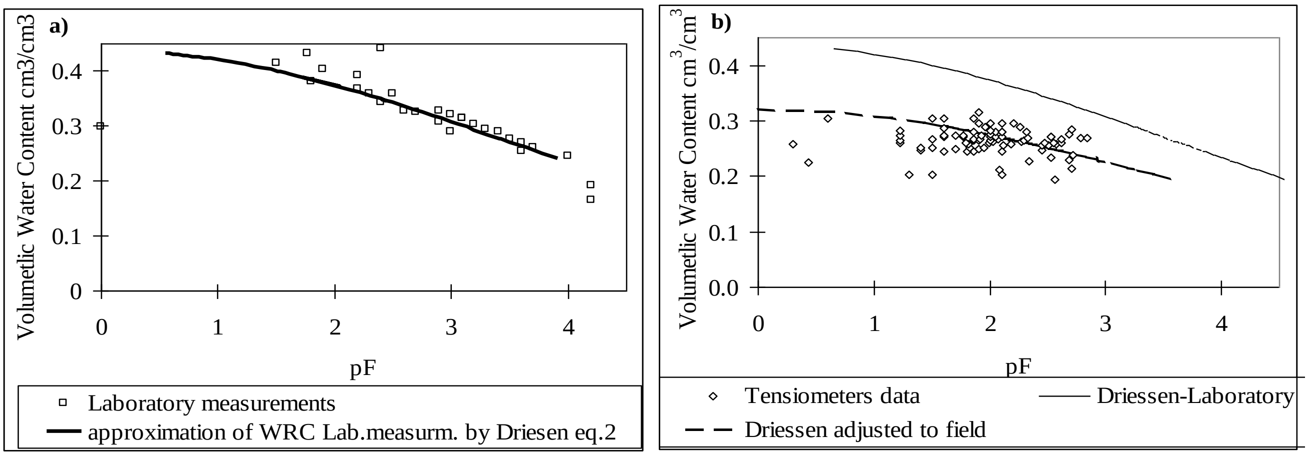

Figure 1. *Calibration of WRC (eq.2) for the clay layer (33-70 cm) in Chelopechene site:**a)** Derivation of parameters from laboratory measurements (step i); **b)** adjustment of eq.2 to field tensiometers readings in 1995/96/97**(**step ii).*

Table 3. *Parameters of WRC (Eq.2) and WCC (Eq.1) after calibration step (i) and step (ii) in Chelopechene.*

Parameter	A-Eq.1	θsat (Eq.1 and 2)		γ (Eq.2)
Method		Laboratory Step (i)	Field Step (ii)	Laboratory and field Step (i)and step (ii)
	-	cm3/cm3	cm3/cm3	cm-2
A-horizon	199.0	0.440	0.370	0.0124
B-horizon	150.0	0.437	0.318	0.0074

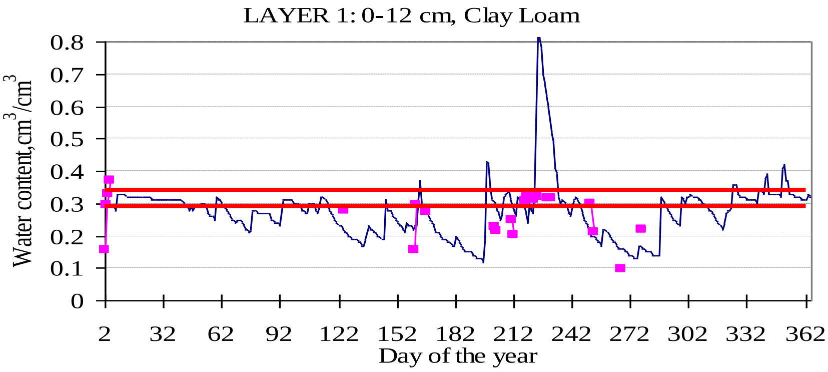

Figure 2. *Measured and simulated (before introduction of preferential flow looping in the model code) water contents for the top soil layer (0-12cm) in Chelopechene (1.Jan.-31.Dec.1997). Two horizontal thick lines represent field capacity and saturation of the layer.*

Introduction of preferential flux looping in the modified version used in this study improved model predictions of soil water in the top layer (Fig.3-b) by redistributing immediately the excess of water above saturation there in the deeper layers (Fig.3-c and Fig.3-d).

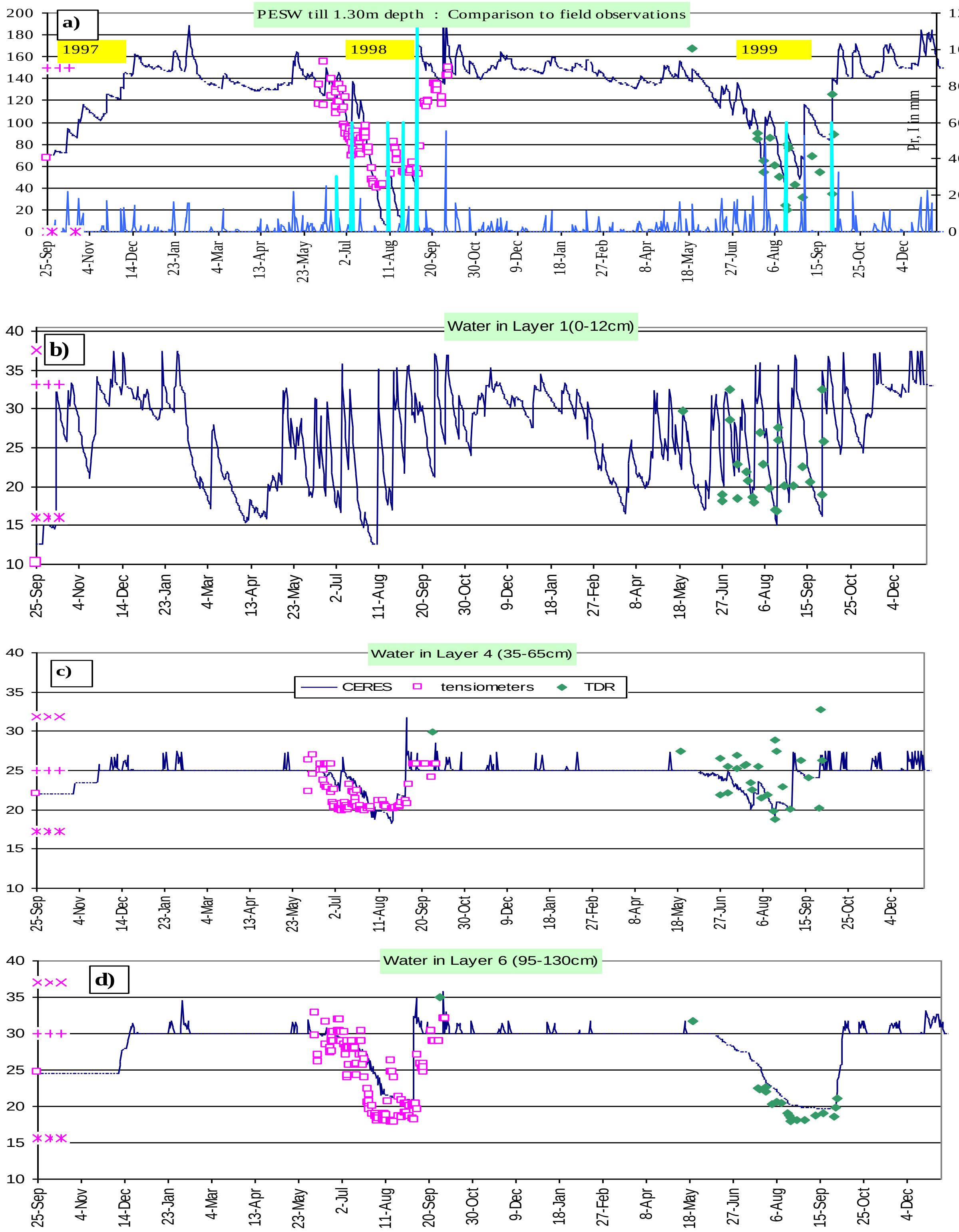

Figure 3. *Comparison between observed and predicted (after calibration) PESW(mm) and soil moisture content SW(% v/v) under maize in Chelopechene (25.Sept.1997-1.Oct.1999) in soil layers 0-12, 35-65, 95-130cm. Symbols correspond to PESW/SW at: ***-WP, +++ FC, xxx-saturation of soil layers.*

Using optimized parameters after calibration, the model was run from 25.09.1997, starting on specified initial soil water content values, till 6.10.1999 (Fig.3). The agreement between model simulation lines of potentially extractable soil water in 1.30m-root zone (PESW) in Fig.3-a and soil water content in different genetic layers (Fig.3-b,-c,-d) on the one hand and field observations (presented in symbols) over two consequent full "fallow state vegetation" cycles showed the acceptability and accuracy of optimized parameter set. Figure 3 proved the overall ability of modified and calibrated soil water balance subroutine of CERES-maize model to predict the redistribution of water input, as precipitation and irrigation, in the soil layers and thus water disposal for crop growth without any further adjustments of the model parameters.

Improvements of model biological prediction

Functions of root water absorption-RWA (eq.3) and crop growth were tuned to lysimeter observations of evapotranspiration and dry weights in calibration step (iii). The initial calibration test against biological data from lysimeter №2, 1997 showed that, nevertheless that soil water physical transport was correctly simulated, model predictions were not correct. RWA function (eq.3) was adjusted to the local higher capacity of the root system to extract water by modification of the power 5 (eq.3) to 3. The latter change in the model code resulted in acceptable agreement between model output and observed evapotranspiration (lysimeters № 1 and № 2 in Fig.4.) and crop dry weights in 1997. It should be noticed that measuring equipment, water balance and dry weights estimates in both lysimeters are completely independent.

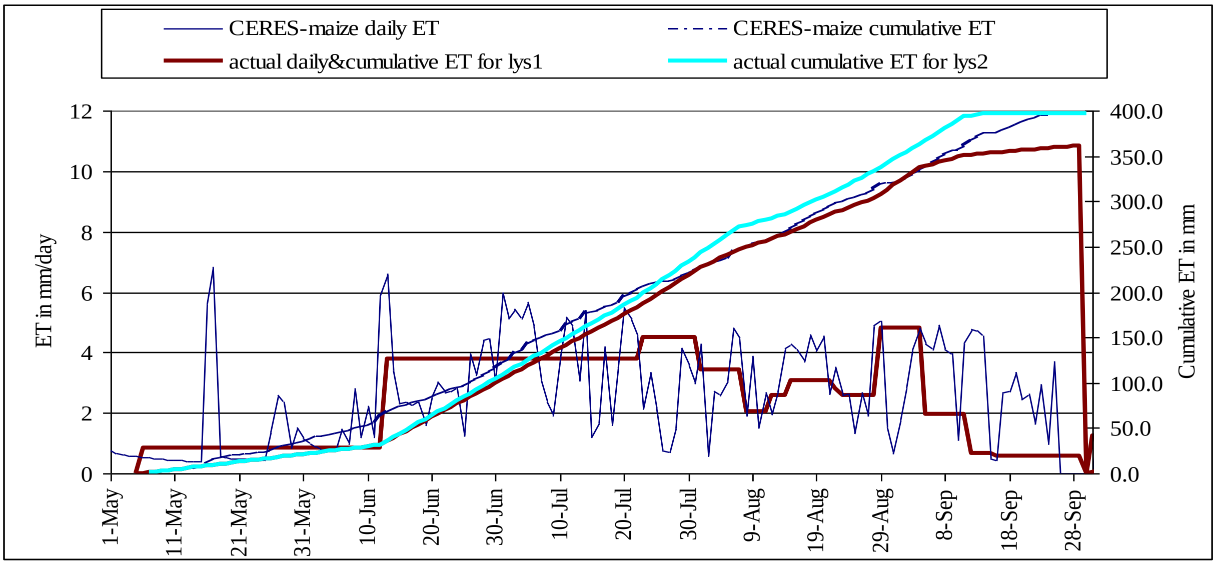

Figure 4. *Comperison between predicted ET (after adjustment of eq.3) and actual ET from water balance data, lysimeter №1 and lysimeter №2, Chelopechene 1997.*

Calibrated biological functions were validated then for a similar situation for the next years (1998 and 1999). Overall graphical model test against three-year independent lysimeter data was illustrated towards water uptake in Fig.5 and dry weights of crop in Fig.6. Actual crop evapotranspiration, as obtained from lysimeter observations, was plotted in stepped thick line for the daily rates (Fig.5) and in symbols for cumulative terms. Actual ET (thick lines in the Fig. 5) was compared with corresponding simulated one after RWA (eq.3) calibration (fine lines).

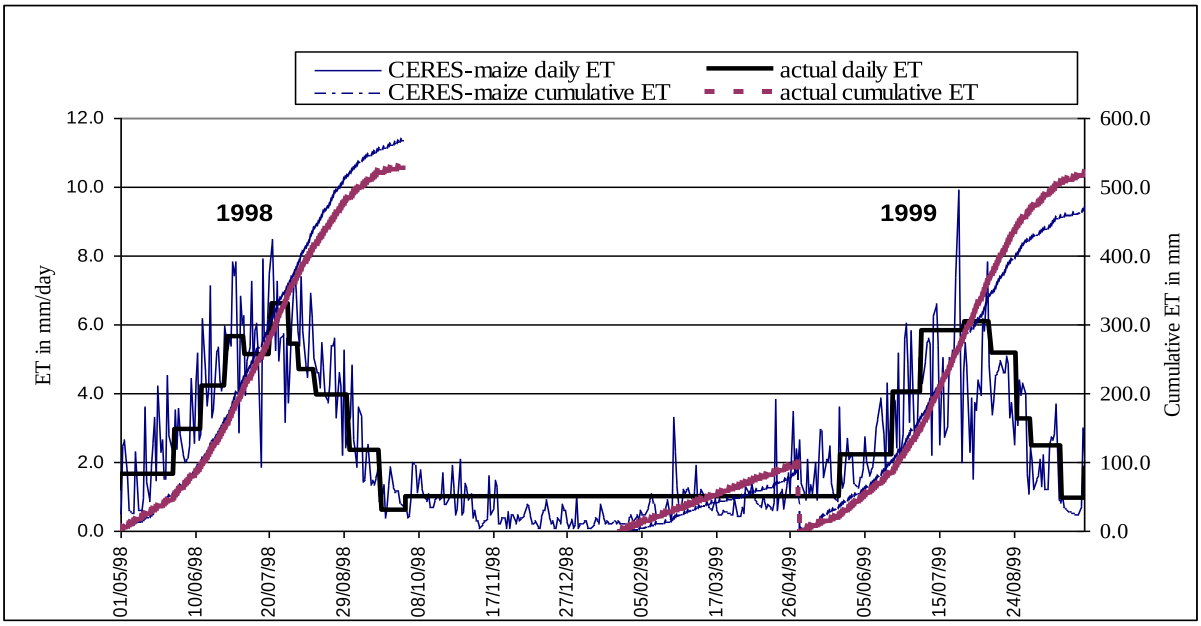

Figure 5. *Validation of modified root water absorption function (eq.3) by comparing predicted to observed evapotranspiration (1.May.1998-1.Oct.1999) in lysimeter №1Chelopechene.*

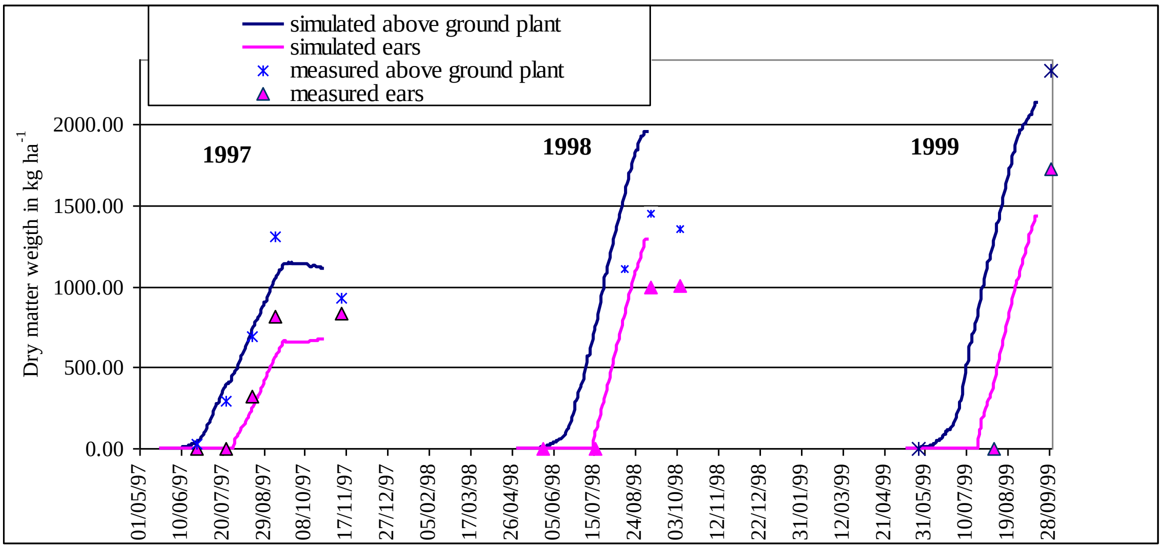

Figure 6. *Validation of crop growth functions by comparing predicted to observed dry weights of maize (1.May.1997-1.Oct.1999) in lysimeter №1 Chelopechene.*

Experimentally obtained dry weights of the crop partitioned to ears and total above ground plant were presented in symbols in Fig.6 while lines were validated model simulations. The agreement between observed and predicted maize evapotranspiration and dry weights (from 1.May 1997 till 1.Oct.1999) was acceptable. Since the vegetation period in 1997 (140 days) was shorter then the following ones in 1998(160 days) and 1999(156 days), cumulative maize evapotranspiration was 362 mm in 1997, 528 mm in 1998 and 518mm in 1999. This difference was mainly due to the later planting date in 1997. Model capability to predict evaporation from bare soil was proved by comparison of observed and predicted cumulative ET in fallow state (from 20.01. to 1.05.1999).

Conclusion

The use of the procedure of stepwise calibration and validation, consisting of comparing model output to observed three-season biological data from lysimeters, enabled to improve the prediction capacity of modified CERES-NC-maize model under Bulgarian conditions. Overall model performance evaluation was provided by graphical methods applied in all steps of model test. The stepwise calibration procedure, starting with transport of water, followed by crop growth and root water absorption, improved parameters' set and biological predictions for the situation under study. As a result of model code modifications and adopted calibration methodology simulation output proved to be accurate enough over a comparatively long period (1.05.1997-1.10.1999). Model simulated acceptably water transport, including preferential fluxes, maize evapotranspiration, evaporation from bare soil and dry weights. The modifications of the modules of soil water and crop growth and derived input parameter set of CERES-maize model would make more plausible risk assessment of environmental impacts and consequences of drought under maize in studied pedoclimate combination.

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