Modeling crop response to soil salinity : review and proposal of a new approach

Castrignanò A., Katerji N., Mastrorilli M.

in

**Katerji N. (ed.), Hamdy A. (ed.), van Hoorn I.W. (ed.), Mastrorilli M. (ed.).
Mediterranean crop responses to water and soil salinity: Eco-physiological and agronomic analyses**

Bari : CIHEAM
Options Méditerranéennes : Série B. Etudes et Recherches; n. 36

2002
pages 251-280

To cite this article / Pour citer cet article

Castrignanò A., Katerji N., Mastrorilli M. **Modeling crop response to soil salinity : review and proposal of a new approach.** In : Katerji N. (ed.), Hamdy A. (ed.), van Hoorn I.W. (ed.), Mastrorilli M. (ed.). *Mediterranean crop responses to water and soil salinity: Eco-physiological and agronomic analyses.* Bari : CIHEAM, 2002. p. 251-280 (Options Méditerranéennes : Série B. Etudes et Recherches; n. 36)

Modeling crop response to soil salinity: review and proposal of a new approach

A. Castrignano'[1], N. Katerji,[2] M. Mastrorilli[1]

Mathematical models prove to be an useful tool to define the best water management in saline conditions. A review of the most known existing models is given in the paper. They can be divided into two main groups: seasonal models, based on an equation that relates yield to the amount of applied irrigation water of a given salinity; transient models, following a mechanistic approach, but generally simplistic in crop dynamics. A new crop-based model for water salinity management is proposed to rectify deficiencies in existing models with respect to crop response to salinity. The CERES-Maize model was modified in the original water uptake term for assessing salinity effects on crop. Reasonable agreement was found between model predictions and experimentally measured data for crop evapotranspiration, biomass, LAI and grain yield. The model may represent a valid tool for salinity risk evaluation.

Keywords: CERES-Maize model, predawn leaf water potential, water and salinity stress.

1. INTRODUCTION

In arid and semi-arid parts of the world, where much of the crop production is under irrigation, there is an increased demand for water by nonagricultural users. To optimize irrigation management, information about crop-water production function is required, particularly when the irrigation waters contain significant amount of

---

[1] *Castrignanò and Mastrorilli: Istituto Sperimentale Agronomico, Via Ulpiani 5, 70125 Bari (Italy) AGROBARI@INTERBUSINESS.IT;*

[2] *Katerji: INRA-Bioclimatologie, 78850 Thiverval-Grignon (France).*

soluble salts which can affect crop production if not properly managed. Management of saline water must be oriented to minimize the potential pollution of the ground water as well as to provide an adequate environment for plant roots. Historically, optimum salinity control consisted in applying convenient amounts of saline water for leaching in addition to evapotranspiration (Letey *et al*., 1985).

Recent studies have demonstrated the necessity to quantify the movement of salts in the root zone and the effect of irrigation water salinity on crop yields (Rhoades, 1974; Hoffman and van Genuchten, 1983). Moreover, quantification of water salinity effects on yield is complicated by the dynamism of water and solutes movement in the soil, spatial variability of soil properties and temporal variability in climatic conditions (Prendergast, 1993). Where experimental work is required to determine the effects of salinity on the soil-plant-atmosphere interactions, only mathematical models can help to integrate these interactions and be an useful tool to define the best management of a system for saline conditions (Ferrer et al., 1995).

Models of crop responses to salinity have multiplied in the past few years. This has come because of the need to look at the large number of factors that influence crop response to irrigation in a world of increasingly scarce and polluted water supplies. The response to this need has been facilitated by the widespread availability of computers and analysis techniques which can handle complex systems.

Models can be considered as an organized expression of knowledge about the interacting factors in a given system. Present day models use simplifying assumptions to replace the details of plant response to the environment with less complex relationships. We will concentrate in this paper on developed models to predict crop yield response to soil water management and salinity when primarily related to irrigation water.

2. STATE OF THE ART

Models available in literature vary greatly, from very simple to sophisticated, from crop specific to general and from primarily crop-based to soil-based. Reviews of existing models are given by Molz (1981) for soil-based models and by Jones and Ritchie (1990) for crop-based models. They can be divided into two main groups: seasonal and transient models (Hoffman et *al*., 1990).

2.1 Seasonal models

Seasonal models are essentially based on an equation that relates yield to the amount of seasonal applied water of a given salinity or to the evapotranspiration and employ very simple methods of calculating water and solute movement in soil profile. An example of a seasonal model is that one developed by Letey *et al*., (1985) for the computation of crop-water production functions with saline irrigation waters. The model combines the three following relationships: yield and evapotranspiration; yield and average root zone salinity, average root zone salinity and leaching fraction. It also allows a plant growth adjustment and therefore an evapotranspiration adjustment to root zone salinity.

The validity of such a model is severly restricted to the set of conditions assumed in the model development, such as kind of relationships between markatable yield and evapotranspiration (supposed to be linear), fertilizer application and drainage (assumed to be adequate), irrigation water (supposed of a constant electrical conductivity).

Most recently, Royo and Aragüés (1992) described the sigmoidal growth response of plants to salinity, by the following non linear model (van Genuchten, 1983):

$$Y = \frac{Y_m}{\left[1+\left(\frac{EC_{sw}}{EC_{50}}\right)\right]^p} \qquad (1)$$

where Y is the yield obtained for a given electrical conductivity, Y_m is the yield under nonsaline conditions, EC_{sw} is the average salinity of applied water, EC_{50} is the salinity of applied water that reduces yield by 50% and p is an empirical constant. This equation can also be expressed in term of relative yield Y_r, where $Y_r = Y/Y_m$. Estimation of model parameters is performed by nonlinear least squares techniques, which reduces the universality of the model application.

Figure 1 shows an example of the existing relationship between yield and average soil salinity, for some crops grown in lysimeters over several years (after Katerji et al., 1994).

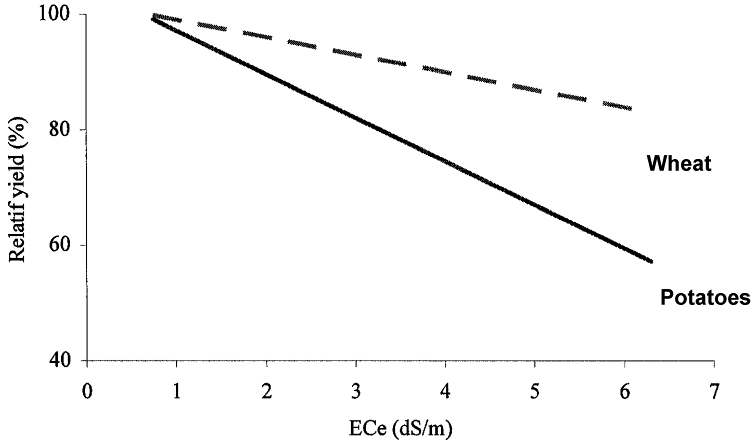

Fig. 1. Relationship between relative yield of potato and wheat versus soil salinity

The main advantage of seasonal models is their semplicity and the major disadvantage consists in the ratio EC_{sw}/EC_{50} which is not a constant value, but it changes for each species as a function of climate, soil type, irrigation management, drainage (Katerji et al., 1995). As a conclusion, the results provided by this kind of approach can not be generalized.

2.2 Transient models

Transient soil-based models generally use sophisticated numerical solutions of water and solute movement and can predict, also with great detail, soil profile conditions. However, the presence of crop roots in the soil is treated as a simple sink term and plant growth dynamics is generally not considered.

One of the earliest detailed quantitative studies of water extraction by plants was that of Gardner (1964) which considers a root to be an infinitely long cylinder of uniform radius and water absorbing properties. The steady-state soil water flow equation was then solved analytically assuming radial flow, and various water potential distributions surrounding the root were calculated.

The works conducted by Whisler *et al*., (1968), Molz and Remson (1970) suggested that the Darcy-Richards equation can be combined with a sink term representing water extraction by plant roots. This approach results in an equation given by:

$$\frac{\partial \theta}{\partial t} = \nabla \left(K_s \nabla \Psi_s \right) - S \qquad (2)$$

where θ is the volumetric soil water content (cm^3 cm^{-3}), t is time (second), ∇ is the gradient operator, K_s is soil hydraulic conductivity (cm^2 s^{-1} bar^{-1}), Ψ_s is soil water potential (bar), and S is the water extraction function (cm^3 cm^{-3} s^{-1}) by plant roots, which can depend on space, time, water potential, water content, or a combination of these variables.

Over the past twenty five years, many authors have developed or applied dynamic models based on one or two-dimensional version of equation (2).

As discussed by Molz and Remson (1970), it is not practical to develop models of water transport at micro-scale, because the detailed geometry of the system is practically impossible to measure and is time dependent. As a consequence, most extraction functions have been developed using a macroscopic as opposed to a microscopic approach.

The most important difference among the several models developed for simulation water and solute transport in soil containing roots is the selected form for the extraction function.

Hanks and co-workers (Nimah and Hanks, 1973) have described such a model for one-dimensional soil water flow, as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} K(\theta) \frac{\partial H}{\partial z} + S(z) \qquad (3)$$

where K(θ) is the hydraulic conductivity of the soil, θ is the volumetric soil water content, t is time, z is soil depth, H is the hydraulic head which is equal to the sum of matric and gravitational head, and S(z) is a root extraction term. The root extraction term is given as:

$$S(z) = \frac{[H_{root} + (1.05\,z) - h(z,t) - s(z,t)]\,RDF(z)\,K(\theta)}{\Delta x\,\Delta z} \qquad (4)$$

where H_{root} is the internal root pressure head at the soil surface, where z is considered zero; the term "$1.05z$" is a correction factor to the root pressure head at other soil depths, h is the matric head, s is the osmotic head which accounts for salinity, RDF is the root density function, Δx is the distance from the root surface to the point in the soil where h(z,t) and s(z,t) are measured and Δz is the depth increment.

The root extraction term includes the salinity effect if the main salinity effect is osmotic only. It is also necessary that the associated flow of salt be accounted for. This is done by solving the following salt flow equation (Bresler, 1973):

$$\frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta, q)\frac{\partial C}{\partial z} + qC\right] \qquad (5)$$

where C is salt concentration, D(θ, q) is a combined diffusion and dispersion coefficient, and q is volumetric water flux as discussed in more detail by Childs and Hanks (1975).

A quite similar expression for the root extraction term was developed by Bresler and Hoffman, 1986):

$$\mathrm{S}(\mathrm{z},\mathrm{t}) = -\mathrm{b}(\mathrm{z})\,\mathrm{K}\left[\theta(\mathrm{z},\mathrm{t})\right]\left[\Psi(\mathrm{t}) - \mathrm{h}(\mathrm{z},\mathrm{t}) - \gamma\,\mathrm{C}(\mathrm{z},\mathrm{t})\right] \qquad (6)$$

where S is the volumetric rate of water uptake by plant roots per unit volume of soil; z is the vertical space coordinate, θ is the volumetric soil water content, t is time, K is the hydraulic conductivity function; Ψ(t) is the total pressure head equivalent in the plant root at the root-soil interface, h is the soil matric pressure head, C the solute concentration and γ is a coefficient which transforms salt concentration units into the appropriate pressure head units. The coefficient of proportionality b represents the geometry of the flow to the roots. γ C represents the osmotic component of the soil-water potential and describes the effects of soil salinity on water uptake by plant roots. When the osmotic potential is low (salt concentration is high), plants may not be able to extract sufficient water and then they transpire less than potentially which may cause a reduction in the yield.

The model considers also a critical, or limiting, value h_{lr}, that represents the lowest possible value for total plant root potential (Ψ). In equation (6), when $h(z,t) + \gamma C(z,t) \leq h_{lr}$, S = 0 and water extraction by roots ceases.

The most recent models simulating water uptake under saline conditions (Kool and van Genutchen, 1991; Cardon *et al*., 1992; SWAP, 1993-1994) use quite similar expressions of the equation relating water extraction to soil matric and osmotic pressure, developed from a work by van Genuchten and Hoffman (1984), having the general form:

$$S = \frac{S_{max}}{1 + \left(\frac{ah + \pi}{\pi_{50}}\right)^3} \qquad (7)$$

where S is water uptake (d^{-1}), S_{max} is maximum water uptake for no-stress conditions ($d^{-1)}$, h is the soil matric head (cm), π is the osmotic head (cm), π_{50} (cm) is the osmotic head that results in a 50% reduction of S_{max}, and *a* is a coefficient equal to π_{50}/h_{50} where h_{50} is the matric head that results in a 50% reduction of $S_{max..}$ The factor S_{max} is related to maximal transpiration T_{max} (cm d^{-1}) of a crop by:

$$S_{max} = T_{max} / L \qquad (8)$$

where L is the rooting depth (cm). Potential transpiration of a crop is a combination of climatic reference evapotranspiration and an associated crop coefficient.

Van Genuchten (1987) proposed the following equation for water uptake at various depths in the soil:

$$S(z)=\left[\frac{S_{\max}}{1+\left(\frac{ah+\pi}{\pi_{50}}\right)^{3}}\right]\lambda(z) \qquad (9)$$

where S(z) is the crop water uptake at depth z and λ(z) is a depth-dependent root distribution coefficient depending on L.

For season-length simulations, S_{max} and L are time-dependent functions dictated by climatic and soil profile conditions. Moreover, many crops exhibit differential tolerance to soil moisture deficit and salinity stress at various growth stages.

Cardon and Letey (1992), by modifying equation (9), obtained the following time and space-dependent water uptake equation which accounts for basic plant growth dynamics, grow-stage-specific stress tolerance and stress-induced growth reduction:

$$S(z,t)=\left[\frac{S'_{max}(t)}{1+\left(\frac{a(t)h+\pi}{\pi_{50(t)}}\right)^{3}}\right]\lambda(z,t) \qquad (10)$$

where S'_{max} (t) is the stress-adjusted value of S_{max}.

Also the rooting depth, L, of a crop may be reduced due to water or salinity stress, but Cardon and Letey's model does not include a complex rooting routine capable to simulate root dynamics, given the empirical nature of the water uptake equation. Moreover, this model is quite simple as to crop growth and does not consider interactions with environmental variables.

Ferrer and Stockle, 1995 modified CropSyst model (Stockle et al., 1994) in order to analyze crop response under saline conditions. The model follows a mechanistic approach and uses Richard's equation for water transport and a convective equation for solute transport.

The soil profile is divided into elements separated by nodes, at which soil water potential, water content, salt concentration and root fraction are defined.

At each node i, water uptake term is approximated as:

$$S_i = K_t \frac{RC_i}{1.5}\left(\Psi_s - \overline{\Psi}_{le}\right) \qquad (11)$$

where S_i is the water uptake, K_t is a constant (86,400 day^{-1}), RC_i is the node root conductance, Ψ_{si} is the soil water potential and $\overline{\Psi}_{le}$ is the average crop canopy leaf water potential.

The root conductance is obtained from:

$$RC_i = f_i RC_{\max} f_{c\,\mathrm{int}} \qquad (12)$$

where f_i is the fraction of total root length present at the node i, RC_{max} is the maximum total root conductance and f_{cint} is the fraction of incident radiation intercepted by the crop canopy.

Salinity effects on crop water uptake are accounted for in two ways; the first effect adds a soil water osmotic potential term to the matric potential and, the second is a reduction of root conductance as salinity increases.

Using a functional form similar to that of van Genuchten (1987), root conductance is modified as follows:

$$\mathrm{RC}_i^{'} = \mathrm{RC}_i \frac{1}{1+\left(\frac{\Psi_{\mathrm{soi}}}{\Psi_{\mathrm{so}50}}\right)^{\mathrm{P}}} \qquad (13)$$

where Ψ_{soi} is the soil osmotic potential at the node i, $\Psi_{so_{50}}$ is the osmotic potential at which crop yield is reduced by 50% and P is an empirical parameter that measures the crop sensitivity to salinity.

Even if this last model represents a great effort to simulate the effects of salinity on the crop, it remains quite simple as to root growth and photosynthetate accumulation. Effectively, moving from physical model, it shows some effort for simulating root absorption under salinity conditions, but the consequences of water constraints originated by salt presence into the soil on plant behaviour appear empirical and very close to the approach of seasonal models whose weakness was just pointed out.

3. PROPOSAL OF A NEW APPROACH

The purpose of this study was to use, or modify, and then test some of existing models for predicting crop response to various combinations of irrigation water quality, soil profile and meteorological conditions. Owing to the abundance of available models, the process of selecting a candidate model resulted quite difficult. We rejected seasonal models because of their empiricism and their limited applicability; most crop-based simulation models employ very simple methods of calculating water and solute movement in the soil profile and are thus unsuitable for saline water management. Moreover, salinity effects on crop response are generally not treated. Soil-based models, on the other hand, generally use a sophisticated numerical and mechanistic approach to water and solute movement in the soil. However, crop water uptake is calculated by a simple sink term, which is generally an empirical relationship between soil water pressure and root water absorption. Moreover, plant growth dynamics is generally not considered or is dealt in a quite simplistic way.

CERES-Maize is a family of crop specific models aimed at dynamic simulation of crop growth and how it is influenced by climatic, plant and soil properties along with some farm management practices (Ritchie, 1985). It was developed as an user-oriented model so its main features are: a) availability of input information on either soils and crop genetics; b) minimal request of computational time.

In order to simplify the model as much as possible many rational empiricisms were used to incorporate information from several levels of organisation in order to simulate in a balance way a community of plants growing in a field. Therefore, CERES model requires an accurate calibration and sometimes a modification of the several empirical equations included in the model, before running in an operational way.

Nevertheless, because the scope of CERES is to provide yield estimation to users, it deals quite accurately with the factors considered to be most influential in determining final yields. These include:

- phasic development as related to plant genetics, weather and other environmental factors;
- apical development as related to morphogenesis;
- extension growth of leaves and stems;
- senescence of leaves;
- biomass accumulation and partitioning;
- impact of soil water and nitrogen deficits on growth, development, biomass accumulation and yield.

The adverse effects of salinity on yields are not thus included in the model. In order to use CERES-Maize under saline conditions, we modified the original version of the model to account for the salinity effects on the crop.

3.1 Water budget in the original ceres model: potential root absorption and plant demand

Evapotranspiration is calculated in CERES-Maize by separating soil evaporation from transpiration (Ritchie, 1972). Potential evapotranspiration is calculated from the equilibrium evaporation equation, as modified by Priestley and Taylor (1972), combined with an equation expressing the effect of radiation and temperature on equilibrium evaporation. Evapotranspiration is multiplied by 1.1 to account for the effects of unsaturated air. The multiplier is increased to allow for advection, when the maximum temperature is greater than 35°C, and reduced for temperatures below 5°C to acc ount for the influence of cold temperatures on stomatal closure.

The CERES-Maize model calculates potential root water absorption rate considering radial flow to single roots and expressing it as a function only of soil water content and root length density. Root length density and distribution in the soil are estimated on the basis of soil properties and the amount of assimilates partitioned to roots. The total potential root water uptake from the entire rooting zone (TRWU) is estimated as the sum of root water absorption from each soil layer with roots (RWU).

3.2 Water stress

CERES-Maize simulates the effects of soil water deficit on the principal plant functions (photosynthesis, morphogenesis, etc.) by using the stress coefficients, calculated from the soil water balance. The model estimates three coefficients of water stress varying from 0 (maximum stress) to 1 (no stress). They represent a kind of balance between plant demand and soil availability of water:

SWDF1 limits photosynthesis, grain filling and transpiration.

SWDF2 limits apical development as related to morphogenesis of vegetative and reproductive structures and then affects extension growth of leaves and stems.

SWDF limits root growth and extension.

SWDF1 is calculated as the ratio between the potential root water absorption (TRWU) and the potential plant transpiration (EP1), which is set equal to potential evapotranspiration (ETP) when LAI>3. SWDF1 is not allowed to be greater than 1, If the maximum water root absorption exceeds the maximum calculated transpiration rate, the maximum absorption rates from each soil layer are reduced proportionally so that the uptake becomes equal to the transpiration rate. If the maximum uptake is less than the maximum transpiration, the transpiration rate is set equal to the maximum absorption rate.

SWDF2 is estimated from SWDF1 as:

$$SWDF2 = SWDF1 * 0.67 \quad (14)$$

The multiplier 0.67 implies that SWDF2 affects the plant functions more severely than SWDF1 does.

During soil drying, SWDF1 and SWDF2 have a little effect on the plant before a given water content threshold is reached, and then they decrease very quickly till vanishing at wilting point. SWDF1, besides affecting photosynthesis, reduces the allocation of assimilates in the grain during grain filling. That may cause a too severe stress at the grain filling stage, because SWDF1 operates at two levels: at the beginning on photosynthesis and then on grain filling.

The morphological effects of water stress are taken into account by SWDF2, which affects leaf area, dry matter of stems and ears, and by SWDF, which affects root system. It needs, however, to point out that the estimation of root growth in the soil is a really weak part of CERES Model since certain assumptions, difficult to verify experimentally, are used for simulation (Ritchie, 1985). Root growth patterns depend really on many physical and chemical soil properties, the amounts of assimilates transported to the roots, and soil water content.

Finally, development is not influenced by water stress in CERES-Maize, which is in contradiction with several experimental trials that have showed the effect of water stress on initiation and differentiation of vegetative and reproductive meristems and on the dates of flowering and silk emission (Robelin, 1984; Plantureux et al., 1991).

3.3 Modification for taking into account the soil salinity

When the level of dissolved salts in the soil solution becomes excessive, plant growth is reduced. This growth reduction can be related in most cases to the total concentration of soluble salts or osmotic potential of the soil solution and therefore to a reduction in water uptake. However, the reduction in soil water availability due to osmotic potential component is not sufficient to account for reduction in biomass accumulation and grain yield.

Salinity effects on crop response were introduced into the modified CERES model in two ways:

3) modifying the water stress functions by relating them to plant water status;
4) linking the plant water status to soil texture and to soil water salinity.

Although the choice of the two stress factors (SWDF1 and SWDF2) in the original model appears to be logical, nevertheless they are calculated from parameters related mostly to the actual water content of the soil. Therefore, in the original CERES-Maize growth reduction is not directly dependent on plant, but rather on soil water status.

A new stress coefficient SWDF1 was defined as the ratio between the actual and the potential evapotranspiration (absence of both saline and water stress). The substitution of transpiration with evapotranspiration was suggested by the difficulty to separate transpiration from soil evaporation in the case of partial ground covering by the crop. Moreover, expressing the new salinity/water stress coefficient as a function of some direct indications of plant water status seemed to be a more logic assumption. In fact, several experimental results indicate (Denmead and Show, 1962; Dwyer and Stewart, 1984), soil-based measurements do not reflect accurately whether water supply is adequate for the crop, because plant can put different compensation processes into effect. Therefore plant-based measurements of water status would be the most reliable.

The new physiological stress index depends directly on plant water status and only indirectly on soil water content through leaf water potential (fig. 2). We preferred to utilize Ψ_b, the predawn leaf water potential, because:

Ψ_b is a much simpler measurement than other indicators of water status (Dwyer and Stewart, 1984);

Ψ_b integrates the effects of several environmental variables, such as soil water content and vapour pressure deficit, on water stress;

Ψ_b is affected by physiological changes as water stress evolves.

The main drawback consists in data availability; water potential was then estimated by using a calibration curve, expressing leaf water potential measured at predawn as a function of water supply in the entire soil profile.

The advantage of the new definition of the stress coefficient derives from its universality, because it can be roughly considered to be the specific maize response to water stress, as proved by experimental evidence (Dwyer and Stewart, 1984; Bennouna, personal communication), both in greenhouse and field experiments.

As far as the other stress coefficients (SWDF2 and SWDF) are concerned, the original definitions were retained.

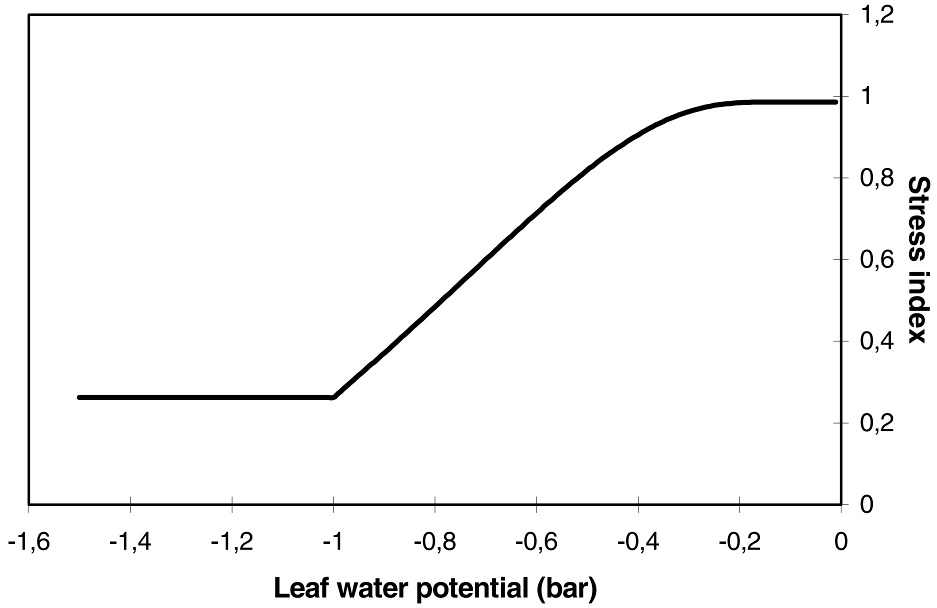

Fig. 2. Relative evapotranspiration vs. predawn leaf water potential

3.4 The calibration of the salinity stress coefficients

The model was tested using data from an experiment conducted on a maize crop at the Mediterranean Agronomic Institute of Bari (Katerji et al., 1996; van Horn et al., 1993). The experimental set-up consisted of 30 drainage lysimeters filled with two types of soil: 15 with a loam or soil A, and 15 with clay or soil B, both irrigated with water of three different qualities: local fresh water containing 3.7 meq l^{-1} of $[Cl^{-1}]$ as a control (A0 and B0), and two levels of saline water of 15 and 30 meq l^{-1} of $[Cl^{-1}]$ (A15, B15 and A30, B30).

Leaf water potential was measured at dawn before sunrise in the upper part of the canopy. Five leaves per treatment were taken from the five replicates, and the water potential was measured with a pressure chamber (Scholander *et al.,* 1965).

Cumulative evapotranspiration, in mm, was calculated over a period between two successive irrigations, when drainage stopped, by applying the soil water balance equation:

$$ET = P + I - D \pm \Delta W \qquad (15)$$

where P is precipitation, I irrigation, D drainage, and ΔW is the difference in water storage of the soil profile, all expressed in mm. In our case, P and ΔW are equal to zero.

Soil water content at the time prior to each irrigation was estimated by subtracting the cumulative evapotranspiration between two successive irrigations from maximum soil water capacity (the soil supposed at field capacity after each irrigation and at the end of drainage). The value so obtained in mm was then converted in volumetric water content.

Leaf area and dry biomass accumulation were determined at each phenological stage, by sampling five plants per treatment, first measuring leaf area ($cm^2\ plant^{-1}$) and then dry biomass ($g\ plant^{-1}$) by oven drying at 75° C for 48 hours. The yield was evaluated as oven-dry weight of the grain at the harvest date.

3.5 Parametrization

A non-linear segmented function was fitted to the relative evapotranspiration and ψ_b (in MPa) data collected in an independent trial by Katerji et al. (1994):

$$\mathrm{SWDF1} = b_0 + \frac{b_1}{\left[1 - b_2 \times \exp(c)\right]} \qquad \text{for } \psi_b \leq -1$$

$$(16)$$

$$\mathrm{SWDF1} = b_0 + \frac{b_1}{\left[1 - b_2 \times \exp\left(\frac{-c}{\psi_b}\right)\right]} \qquad \text{for } \psi_b > -1$$

where b_0, b_1, b_2 and c are empirical coefficients.

The stress function [16] was calculated using a non-linear fitting procedure to produce least-square estimates and asymptotic standard errors of the coefficients and mean square error of the model. The peculiar analytical form of [16] was chosen because, unlike an index operating exclusively by a "threshold effect", it allows to simulate a progressive reduction in physiological functions as water stress increases. On the contrary, in the original CERES-Maize model the stress index begins to decrease very quickly starting from a given critical value of soil water content.

Then, we calibrated ψ_b as a function of relative total water supply in the soil profile standarised to maximum (TSW) for each type of soil and each salinity level of irrigation water. As regards the salinity levels, they were chosen because they define the salinity range of irrigation water commonly used in agriculture to a profit.

A segmented linear model was fitted to the measurements of water potential:

$$\psi_b = a \qquad \text{for TSW} < b \qquad [17]$$

$$\psi_b = e\,\text{TSW} + f \qquad \text{for } b \leq \text{TSW} \leq d$$

$$\psi_b = c \qquad \text{for TSW} > d \text{ (with } a < c \text{ and } b < d)$$

The standardisation of soil water content was necessary to compensate differences in porosity and texture between the soils. The regression coefficients (a, b, c, d, e and f) in equation [17] were estimated by the linear least-square method (Marquardt, 1983), using lysimetric predawn water potential and soil water content measurements relative to one single drying-up cycle, observed between two successive irrigations.

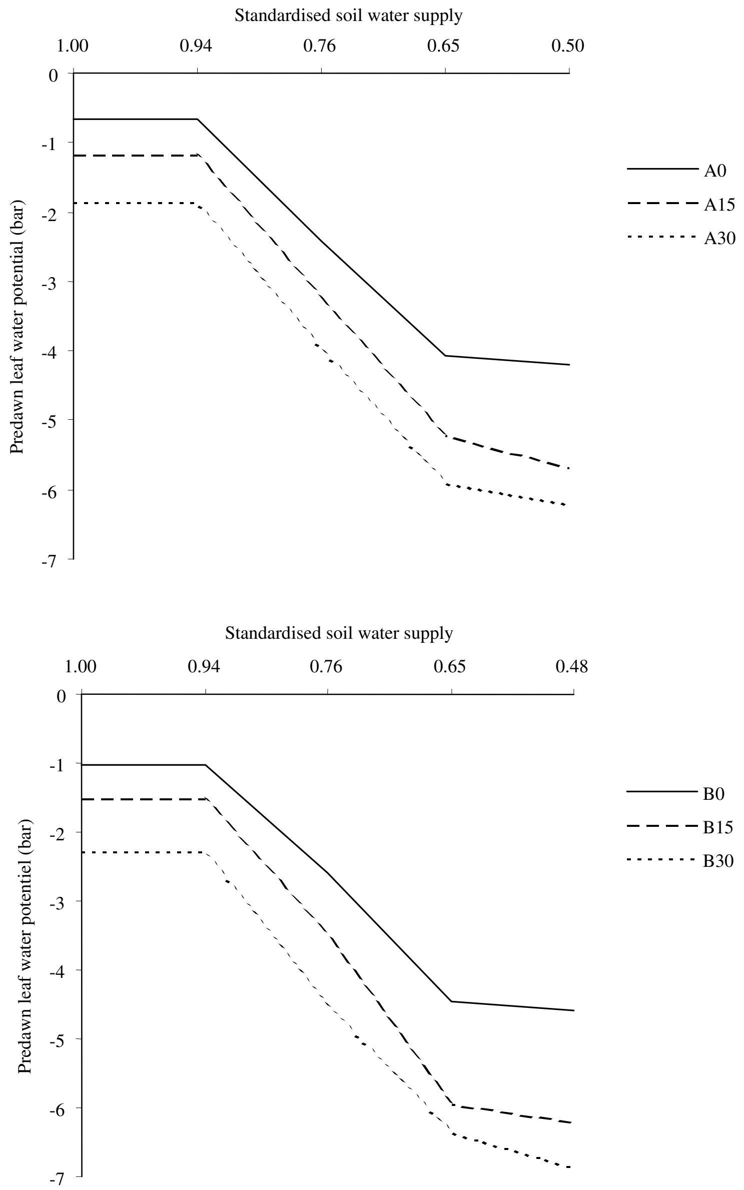

Fig. 3. Calibration curve of predawn leaf water potential vs. standardised soil water supply for each saline treatment and soil type

In Figure 3 the six calibration curves for each combination soil type × salinity level are reported. As it is clear from the figures, water availability to crop decreased as salinity level increased.

3.6 Validation

Phenological dates of the plants grown in the lysimeters irrigated with fresh water were used for setting crop genetic parameters of the model, according to the procedure proposed by Ritchie and Alagarswamy (1989).

Cumulative crop evapotranspiration, cumulative above-ground biomass and the LAI, estimated at the different dates of observation, and final grain yield were chosen as response variables to value the model performance.

The statistical procedure used consisted in a linear regression between averaged predicted and measured values for each of the three variables under study. Two Student's tests were then applied to verify the following two "null" hypotheses: intercept=0 and slope=1.

3.7 Results

Preliminarily, the model was calibrated for the variety Hybrid Asgrow 88 under Mediterranean conditions. The calibration was done by trial and error, changing the genetic parameters in order to match simulated data to phenology (d.o.y. = day of year) and production. The values of genetic parameters are: P1 = 80.00; P2 = 0.30; P5 = 500.00; G2 = 720.00; G3 = 11.00. Some results of simulations, compared with the corresponding measurements for each soil type x water salinity level combination, are the following:

Variable	Units	Treatments (soil x salinity)					
		AD		A15		A30	
		pred.	obs.	pred.	obs.	pred.	obs.
Anthesis date	(d.o.y*)	258	253	258	253	258	253
Maturity date	(d.o.y)	298	293	298	293	298	293
Grain yield	(kg/ha)	6837	6783	5597	6740	5470	5331
Kernel weight	(kg)	0.230	0.244	0.212	0.254	0.212	0.232
Grains per m^2	-	2994	2766	2655	2666	2600	2301
Grains per ear	-	498.98	521.00	442.49	486.00	433.33	505.00
Max LAI	-	3.52	3.42	2.43	3.08	2.41	2.78
Biomass	(kg/ha)	14652	14661	10766	13873	10585	12696
ETR	(mm)	524	520	488	494	484	424
		BD		B15		B30	
Anthesis date	(d.o.y)	258	253	258	253	258	253
Maturity date	(d.o.y)	298	293	298	293	298	293
Grain yield	(kg/ha)	6854	5477	5616	4858	5570	4141
Kernel weight	(kg)	0.230	0.221	0.212	0.226	0.212	0.212
Grains per m^2	-	2998	2467	2662	2150	2646	1951
Grains per ear	-	499.67	526.00	443.64	486.00	441.04	441.00
Max LAI	-	3.53	3.43	2.43	2.98	2.38	2.72
Biomass	(kg/ha)	14683	13236	10794	11915	10715	11332
ETR	(mm)	529	571	484	492	480	448

As regards the two fresh water treatments, the simulation was quite good in terms of yield, above-ground biomass and maximum LAI. However, simulation differed considerably from reality as concerned phenology, as simulated dates for both flowering and physiological maturity lagged five days behind, regardless of treatment. Moreover, as regards saline treatments, an underestimation of maximum LAI was observed, which caused an underestimation in above-ground biomass.

To evaluate the model performance, time paths of simulated evapotranspiration, above-ground biomass and LAI, compared with observed data, are reported on a daily scale for all treatments and for each soil type in Figures 4, 5 and 6, respectively. The overall matching between evapotranspiration simulations and measurements was satisfactory for both soils and all saline treatments, with a slight overestimation during the central phase of the crop cycle for the more stressed treatment. The greatest deviations were observed early in the growth period, from sowing to about day of year 223, when the soil was mostly uncropped upon irrigation. After irrigation, simulated evapotranspiration decreased very quickly from unrealistic high values to very low values in one or two days at most, unlike a natural process which develops more gradually. A probable explanation of such mismatching might be that before crop closing, canopy evapotranspiration is largely affected by soil evaporation, the estimation of which is generally quite difficult since it involves the calibration of some critical coefficients controlling soil drying. Another very likely cause of disagreement between simulation and reality might be the difference in the time interval used to calculate simulated and observed data: the former were predicted daily, whereas the latter were expressed as daily averages over the period between two successive irrigations.

As regards dynamic evolution of cumulative biomass (fig. 5), there were no significant differences between the two kinds of soil, with the exception of a more dramatic effect of simulated salinity stress on the plants cropped in soil B. The agreement between simulation and reality was quite good as regards fresh water treatments; on the contrary, the simulated reduction in biomass caused by salinity stress was too severe, mainly for the less stressed treatment, very likely due to actual partial crop adaptation to salinity stress.

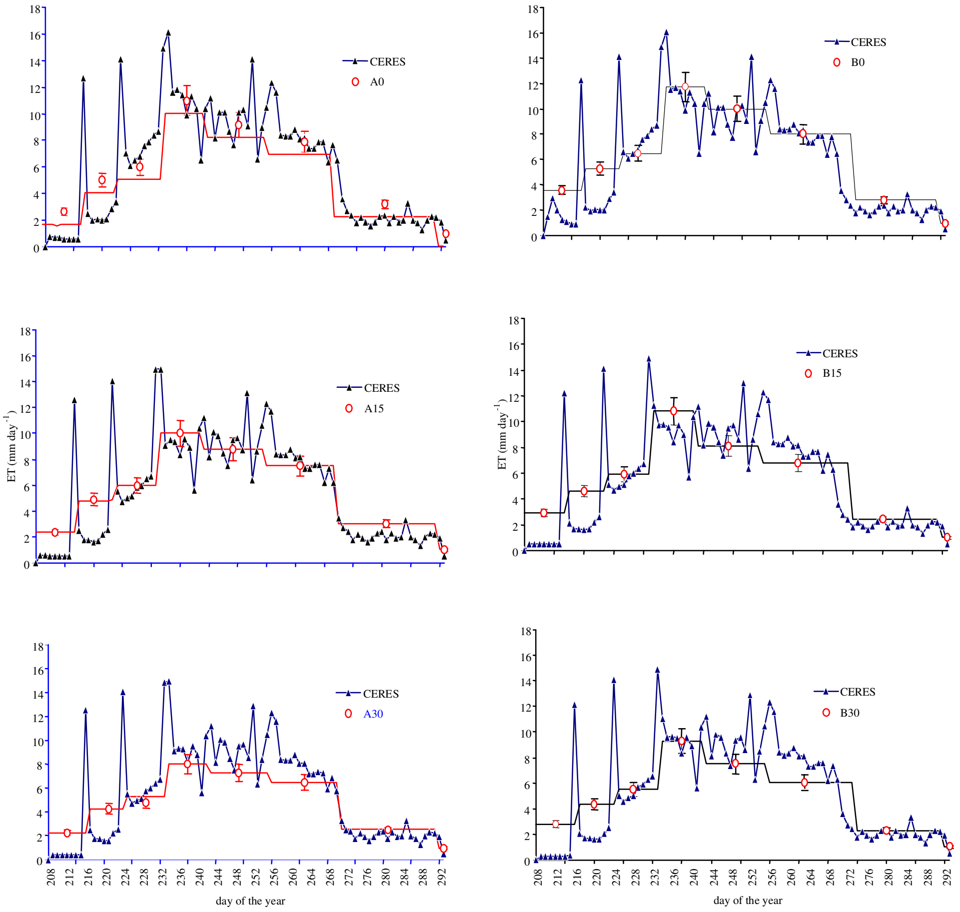

Fig. 4. Comparison between measured and predicted daily evapotranspiration as simulated by CERES-Maize.

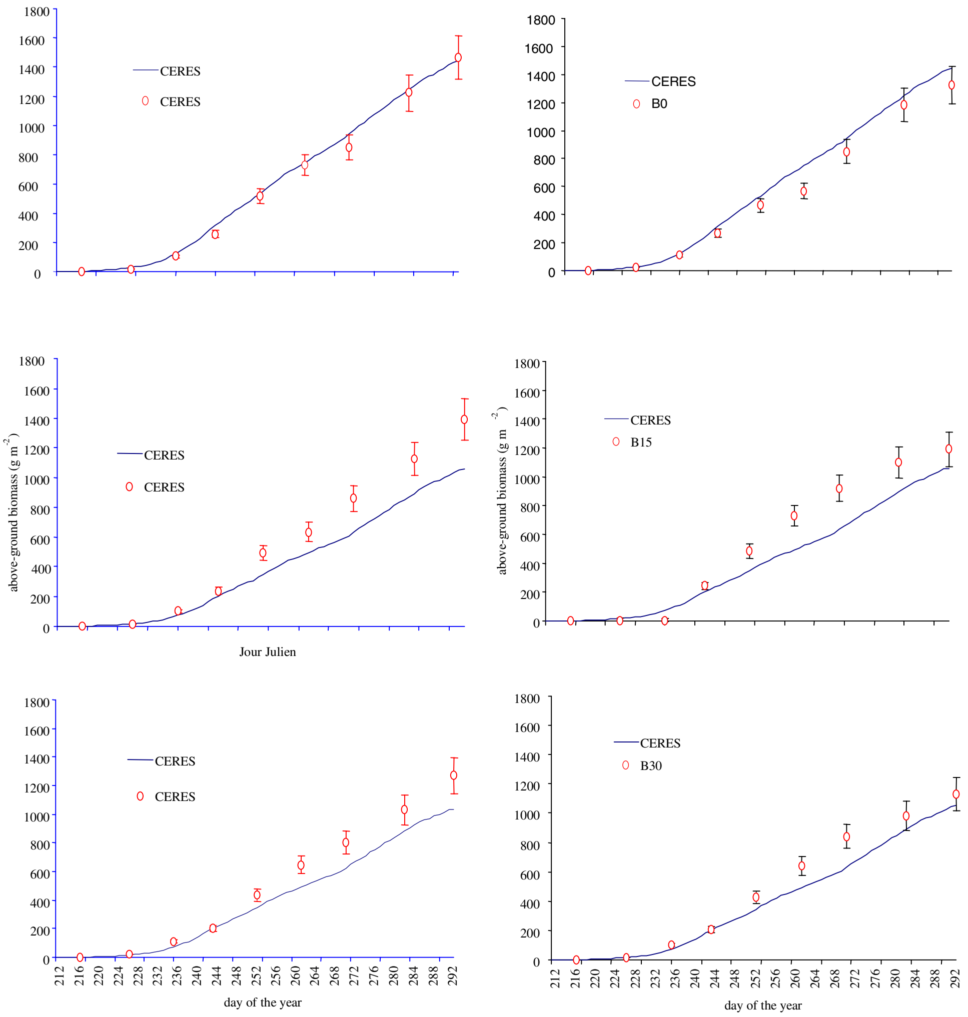

Fig. 5. *Comparison between measured and predicted biomass as simulated by CERES-Maize.*

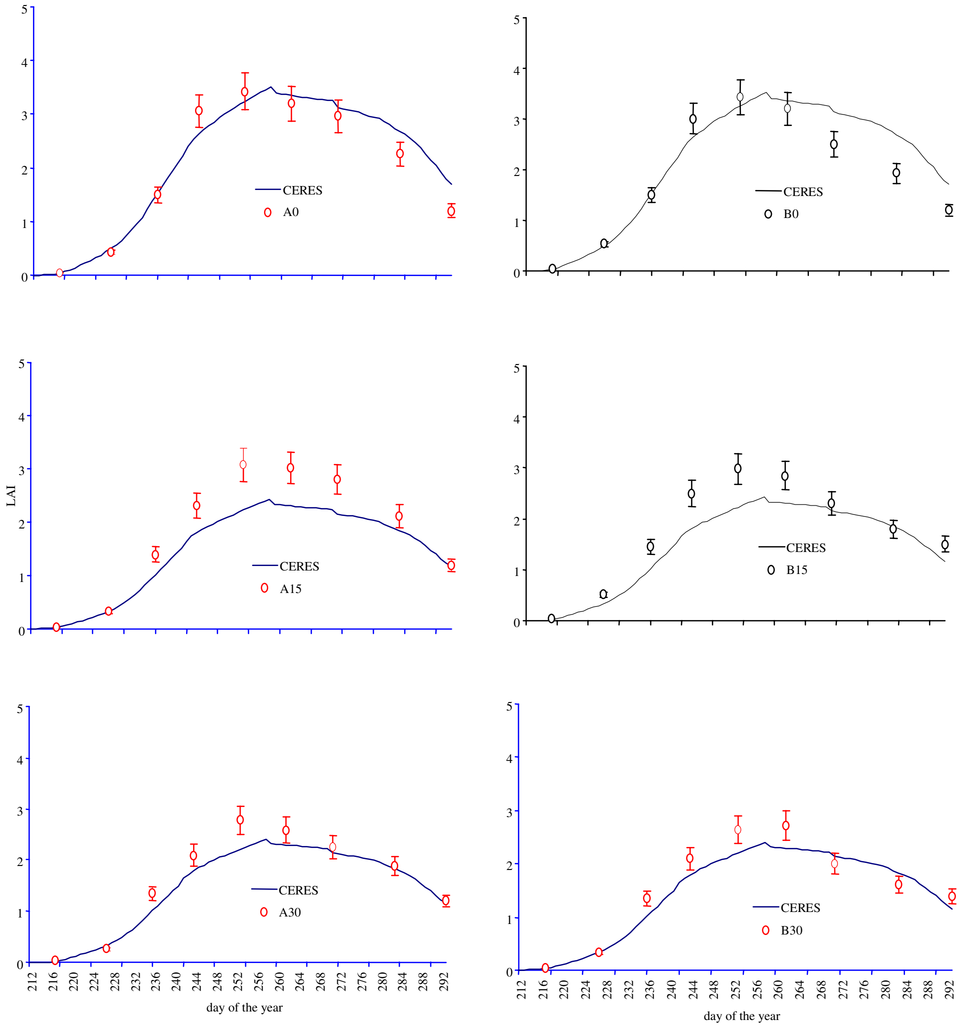

Fig. 6. *Comparison between measured and predicted Leaf Area Index as simulated by CERES-Maize.*

LAI prediction showed the same weakness observed for biomass (fig. 6). Model fitting was quite good for the fresh water treatments, except after flowering when actual leaf senescence developed more quickly than in simulation. A quite reasonable cause of that was the poor simulation of leaf senescence in the CERES model, which produced an overestimation of the amount of actively photosynthesizing green leaf tissues. Again, matching was the worst for the less stressed saline treatment: it seems that the critical threshold value for leaf potential is really lower than the one used in the model.

For a more objective comparison between simulation and reality, a linear regression was performed between the averaged values of predictions and experimental data, in relation to the following response variables: final grain yield, cumulative crop evapotranspiration, cumulative above-ground biomass and the LAI. As regards final grain yield and the LAI, the simulation was quite good, because the intercept and the slope were not significantly different from 0 and 1, respectively. On the contrary, crop evapotranspiration was biased at low values and overestimated of about 8%. The prediction of above-ground biomass was better, because it was not biased and slightly underestimated (less than 1%). The results of this analysis are:

Parameter	Intercept		Slope		R^2 and n[5]
	Estimate	Std Error	Estimate	Std Error	
Final grain yield	-0.204 ns	0.585	1.082[1]	0.115	0.96 (6)
Evapotranspiration	23.488[2]	7.75	0.924[3]	0.027	0.96 (17)
biomass	25.273 ns	1.146	1.077[4]	0.035	0.95 (20)
Leaf Area Index	0.135 ns	0.092	1.002[1]	0.048	0.88 (20)

[1] the slope is not significantly different from 1; [2] the intercept is significantly different from 0 for $p<0.001$; [3] the slope is significantly different from 1 for $p<0.01$; [4] the slope is significantly different from 1 for $p<0.05$; [5] number of observations (within the brackets); ns: the intercept is not significantly different from 0.

The quite high determination coefficients (R^2), with the only exception for the LAI, seem to suggest that the modified CERES-Maize model reproduces well enough the mean performance of a maize crop irrigated with water of salinity ranging within the interval commonly used in Mediterranean agriculture. The rather small determination coefficients for LAI was due, very likely, to a non-linear relationship between simulated and real values.

4.0 CONCLUSIONS

A modification of CERES-Maize model is proposed to predict crop response to salinity stress. The effects of such stress were simulated using soil water deficit factors (SWDF1 and SWDF2), defined as functions of predawn leaf water potential, which was chosen because it represents a synthetic parameter, directly related to plant water status. These factors can affect the simulated plant physiology (photosynthesis) and morphology (growth of tissues); therefore, their definition seems logical, as previous because experimental results (Castrignanò et al., 1998) have proved the similarity between salinity stress and water stress in causing a reduction in biomass and then in production. Actually, the effects of salinity stress predicted by the model were found consistent even if overestimated, particularly as regards biomass and LAI.

In conclusion, the preliminary results of the test of the modified CERES-Maize model can be considered quite satisfactory and encouraging. However, the model needs to be improved in the following:

- increasing model sensitivity to soil type, as it failed to simulate the lower productivity of soil B (more clayey), even in no-stress conditions, due to a reduction in water availability for plants;
- redefining the stress function in the light of further experimental evidence, either in terms of threshold values or analytical form;
- modifying the simulation of the rate processes of leaf-growth and senescence, which will also result in better simulation of biomass and grain yield.

5.0 BIBLIOGRAPHY

AL-KHAFAF, S., ADNAN, A. AND AL-ASADI, N.M., (1990). Dynamics of root and shoot growth of barley under various levels of salinity and water stress. Agric. Water Manage., 18: 63-75.

BRESLER, E., (1973). Simultaneous transport of solute and water under transient unsaturated flow conditions. Water Resour.Res., 9 : 975-986.

BRESLER, E. AND HOFFMAN G.J., (1986). Irrigation management for soil salinity control: Theories and tests. Soil Sci.Soc.Am.J., 50:1552-1559.

CARDON, G. E. AND LETEY, J., (1992). Plant water uptake terms evaluated for soil water and solute movement models. Soil Sci. Soc. Am. J., 32: 1876-1880.

CASTRIGNANÒ, A., KATERJI, N., KARAM, F., MASTRORILLI, M. AND HAMDY, A., (1998). A modified version of CERES-Maize Model for predicting crop response to salinity stress. Ecological Modelling (in press).

CHILDS, S.W. AND HANKS, R.J., 1975. Model of soil salinity effects on crop growth. Soil Sci.Soc.Am.Proc.39: 617-622.

DENMEAD, O.T. AND SHAW, R.H., (1962). Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J., 54: 385-390.

DINAR, A., RHOADES, J.D., NASH, P. AND WAGGONER, B.L., (1991). Production functions relating crop yield, water quality and quantity, soil salinity and drainage volume. Agric. Water Manage., 19: 51-66.

DWYER, L.M. AND STEWART, D.W., (1984). Indicators of water stress in Corn (*Zea mays L.*) Can. J. Plant Sci., 64: 537-546.

FERRER, F. AND STOCKLE, C.O., (1995). A model for assessing crop response and water management in saline conditions. Contribution to the ICID/FAO Workshop on Irrigation Scheduling: From Theory to Practice. 46th IEC Meeting of ICID, Rome, September 1995.

GARDNER, W.R., (1960). Dynamic aspects of water availability to plants. Soil Sci., 89: 63-73.

GARDNER, W.R., (1964). Relation of root distribution to water uptake and availability. Agron. J., 56: 41-45.

HANKS, R. J. AND RASMUSSEN, V. P., (1983). Predicting crop production as related to plant water. Adv. Agron., 35: 193-215.

HOFFMAN, G.J. AND VAN GENUCHTEN, M.TH., (1983). Soil properties and efficient water use: water management for salinity control. In H.M. Taylor et al. (ed.). Limitations to efficient water use in crop production. American Society of Agronomy, Madison, WI 53711:73-85.

HOFFMAN, G.J., RHOADES, J.D., LETEY, J. AND FANG SHENG, (1990). Salinity management. In Management of farm irrigation systems. ASAE Monograph. Ed. by Hoffman, G.J., Howell, T.A. and Solomon, K.H.: 667-715.

HSIAO, T. C., ACEVEDO, E., FERERES E. AND HENDERSON, D. W., (1976). Water stress, growth and osmotic adjustment. Trans. R. Philos. Soc. Lond. B., 273-479.

JONES, J. W. AND RITCHIE, J. T., (1990). Crop growth models. In: G. J. Hoffman et al., (ed.), "Management of farm irrigation system". ASAE Monogr. ASAE, St Joseph, MI., 63-85.

KATERJI, N., (1995). Crop response to saline water stress: empirical and mechanistic approach. Comptes rendus de l'Académie d'Agriculture de France., 81, 2, 73-86.

KATERJI, N., TARDIEU, F., BETHENOD, O. AND QUETIN, P., (1994). Behaviour of Maize Stem Diameter during drying cycles: Comparison of two methods for detecting water stress. Crop Sci., 34: 165-169.

KATERJI, N., VAN HOORN, J.W., HAMDY, A., KARAM, F. AND MASTRORILLI, M. (1996). Effect of salinity on water stress, growth and yield of maize and sunflower. Agric. Water Manage., 30:237-249.

KOOL, J.B. AND VAN GENUCHTEN, M.TH., (1991). HYDRUS. One-Dimensional Variably Saturated Flow and Transport Model, Including Hysteresis and Root Water Uptake. Version 3.31. U.S. Salinity Laboratory. U.S. Department of Agricultural. Agricultural Research Service. Riverside, California.

LETEY, J., DINAR A. AND KNAPP K.C., (1985). Crop-water production function model for saline irrigation waters. Soil Sci.Soc.Am.J., 49:1005-1009.

LETEY, J. AND KNAPP, K., (1990). Crop-water production functions under saline conditions. In Agricultural Salinity Assessment and management. ASCE Manuals and Reports on Engineering Practice. n°17. Ed. by K.K. Tanji: 305-326.

MAAS, E. V. AND NIEMAN, R. H., (1978). Physiology of plant tolerance to salinity. In: G.A. Jung (ed) Crop tolerance to suboptimal land conditions. ASA, Madison, WI, pp 277.

MOLZ, F.J. AND REMSON, I., (1970). Extraction term models of soil moisture use by transpiring plants. Water Resour.Res., 6: 1346-1356.

MOLZ, F. J., (1981). Models of water transport in the soil-plant system: A review. Water Resour. Res. 17: 1245-1260.

NIMAH, M. N. AND HANKS R. J., (1973). Model for estimating soil water, plant and atmospheric interrelations. I: Description and sensitivity. Soil Sci. Soc. Am. Proc., 37:522-527.

MARQUARDT, D.W., (1963). An Algorithm for Least-Squares Estimation of Non-linear Parameters. J. for the Society of Industrial and Applied Mathematics, 11: 431-441.

PRENDERGAST, J.B., (1993). A model of crop yield response to irrigation water salinity: theory, testing and application. Irrig. Sci. 13: 157-164.

PLANTUREUX, S., GIRARDIN, PH. AND VINCENT, G., (1991). Prise en compte du stress hydrique dans CERES-Maize. In: Physiologie et production du maïs, Eds. Picard D., Pau-Paris, AGPM, INRA, pp. 469-476.

PRIESTLEY, C.H.B. AND TAYLOR, R.J., (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev., 100: 81-92.

RHOADES, J. D., (1984). New strategy for using saline waters for irrigation. In Proc. ASCE Irrig. Drainage Spec. Conf., “Water-Today and Tomorrow”. 24-26 July 1984. Flags, taff., AZ.,: 231-236.

RITCHIE, J.T., (1972). A model for predicting evaporation from a row crop with incomplete cover. Water Resources Research, vol 8 (5): 1204-1213.

RITCHIE, J. T., (1985). A user-oriented model of the soil water balance in wheat. In: Wheat growth and modeling. Ed. by Day, W. and Atkin, R. K., Plenum Publishing corporation: 293-305.

RITCHIE, J. T. AND G. ALAGARSWAMY, (1989). Genetic coefficients for CERES Models. In: Modeling the growth and development of sorghum and pearl millet. Ed. by Virmani, S. M., Tandon, H. L. S., and G. Alagarswamy. Research Bullettin N°12. International Crop Resear ch Institute for the Semi-Arid Tropics. Patancheru, India: 27-29.

ROBELIN, M., (1984). Fonctionnement hydrique et adaptation à la sécheresse. In: Physiologie du maïs, INRA, Paris, 445-476.

ROYO, A. AND ARAGUES, R., (1993). Validation of salinity crop production functions obtained with the triple line source sprinkler systems. Agron.J.,85:795-800.

SANCHEZ-DIAS M., APARCIO-TEJO P., GONZALEZ-MURA, C. AND PENA, J. I., (1982). The effect of NaCl salinity and water stress with polyethylene glycol on *N* fixation, stomatal response and transpiration of *Medicago sativa, Trifolium repens* and *Trifolium brachycalycinum* (subclover), Physiologia Pl 54: 361

STOCKLE, C.O., MARTIN, S.A. AND CAMPBELL, G.S., (1994). Crop Syst, a Cropping Systems Simulation Model: Water/Nitrogen Budgets and Crop Yield. Agricultural Systems, 46: 335-359.

STOCKLE, C.O., NELSON, R.L. AND CAMPBELL, G.S., (1995). CropSyst, cropping systems simulation model. User’s manual. Dept. Biological Systems Engineering, Washington State University, Pullman, WA.

SWAP, (1993, 1994). Input instructions manual. DLO-Winand Staring Centre, Wageningen Agricultural University. Rapport 45.

Stewart, J.I., Danielson, R.E., Hanks, R.J., Jakson, E.B., Hagan, R. M., Pruitt, W.O., Franklin, W.T., Riley, J.P., (1977). Optimising crop production through control of water and salinity levels in the soil. Utah Water Research Lab., PR 151-1, Logan, Utah, 199 pp.

SAS INSTITUTE INC., (1997). SAS/Stat user's guide. Release 6.11, Ed. Cary, N.C.

Scholander, P. F., Hammel, H. T., Bradsteet, E. D. and E. A. Hemmingsen, (1965). Sap pressure in vascular plants. Science 148: 339-346.

Van Hoorn, J. W., Katerji, N., Hamdy A., and Mastrorilli. M., (1993). Effect of saline water on soil salinity and on water stress, growth and yield of wheat and potatoes. Agric. water manage., 23, 247-265.

Shalhevet, J., (1984). Management of irrigation with brackish water. In: Shainberg I., and Shalhevet J. (eds.), Irrigation with brackish water-processes and management. Springer, Berlin Heidelberg, New York, pp. 298-318.

Shalhevet, J. and Th.C. Hsiao. (1986). A comparison of their effects on osmotic adjustment, assimilation, transpiration and growth. Irrig. Sci., 7:249-264.

Van den Broek, B.J., Elbers, J.A., Huygen, J., Kabat, P., Wesseling, J.G., van Dam, J.C. and Feddes, R.A., (1994). SWAP 1993 Vakgroep Waterhuishouding. Nieuwe Kanaal 11, 6709 PA Wageningen.

Van Genuchten,M.Th., (1983). Analyzing crop salt tolerance data: Model description and user's manual. USDA-ARS, U.S. Salinity Lab. Res. Rep.120.U.S. Salinity Lab. Riverside, CA.

Van Genuchten, M.Th. and Hoffman, G.J., (1984). Analysis of crop salt tolerance data. Ecol. Stud., 51: 258-271.

Van Genuchten, M. Th., (1987). A numerical model for water and solute movement in and below the root zone. Res. Rep. 121, U.S. Salinity Lab., USDA-ARS, Riverside, CA.

Wagenet, R.J. and Huston, J.L., (1987). LEACHM: Leaching estimation and chemistry model: A proposed based model of water and solute movement, transformations, plant uptake and chemical reactions in unsaturated zone. Continuum Vol. Water Resour. Inst., Cornell Univ., Ithaca, NY.

Whisler, F.D., Klute, A. and Millington, R.J., (1968). Analysis of steady state evapotranspiration from a soil column. Soil Sci.Soc.Am.Proc., 32:167-174.