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THE UNIVERSAL WATER STRESS INDEX IN CULTIVATION OF AGRICULTURAL CROPS

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A b s t r a c t. There are few territories around the world where water availability does not limit the yield of agricultural crops. As a rule, water is the main natural limiting factor, and either water deficiency or its surplus restrict the yield level.

Attempts were made to establish the relations and simulation methods enabling an estimate of the influence of water deficiency stress on the yield formation. An opposite situation, when plants grow under overmoistening conditions, is not investigated. The aim of this paper is to propose a method of simulation of water stress index which unifies the influence of both water deficit and excess on plant growth and development and on the final yield. New method of the simulation of plant transpiration under submergence conditions was proposed and the dynamic simulation model of water balance under agricultural crop was developed for this purpose.

K e y w o r d s: water stress index, crops, simulation of plant transpiration

INTRODUCTION

Agricultural crops undergo some limiting factors in the course of the vegetation period practically in all the regions of the world. The major factors of such a kind are: carbon dioxide, heat, moisture and the elements of mineral nutrition. The oxygen deficiency in the soil air can also restrict the yield by a temporary soil overmoistening. Limiting factors are not constant, but can change in the course of plant vegetation.

In simulation of plant production processes it has become common to take into account these circumstances by distinguishing so-called unconstrained conditions and some stresses superimposed. Classification of the levels of plant productivity proposed by Penning de Vries and van Laar [1] seems to be fruitful for these purposes. Really, uncontrolled natural factors - incoming solar radiation and air temperature - limit the yield only on the first level of productivity, whereas water availability, which refers to the second one, is under human impact by irrigation. The third and the following productivity levels are connected with factors controlled by man since they are determined by fertilization and other agricultural measures.

We will focus our attention on the second level of productivity where soil moisture restricts the yield during a part of vegetation period or the whole one. At moments when soil moisture is optimal, plant development is limited by incoming PAR and, possibly, by the temperature of the air. The last condition would be called unconstrained because regions of temperate climates are considered, where temperature stress is absent.

Many papers were devoted to simulation of the influence of water stress on the production process of agricultural plants. Under water deficit this influence is displayed in a natural way, e.g., through stomata closing, reduction in photosynthesis rate, change in the rate of development and the distribution of assimilates preferentially to the roots. Detailed consideration of water stress on maize cultivated in the U.S. corn belt is contained in Shaw's papers [3,4]. The questions of the influence of submergence on plant production process are rather less investigated. The model developed by Tolstogousov [5,6] is one of the most advanced in this field. A comprehensive analysis of the processes taking place in the soil as well as in the plants by overmoistening is already said there. However, two possible cases, the drought stress and the overmoistening one were considered separately up-to-now. An attempt to join these cases is presented in the paper. A universal form of stress function is proposed. It includes both cases - the influence over production process of the deficiency and the surplus of the soil moisture. Two questions are to be considered: how to describe dynamics of water exchange, first, and how to include an exertion of the moistening condition into the model in order to describe their effect on the yield, second.

MODEL DESCRIPTION

The problem of simulation of water dynamics in a soil, plants and a near-soil air includes two parts. The first one consists in determination of the boundary conditions and the sink function and the second one leads to the choice of an appropriate method of numerical integration of differential equations. We will not discuss the second problem because there are many methods for its solution. Let us only consider the question of the calculation of plant transpiration and water evaporation from the soil surface. These relations form the sink function and the boundary condition of the problem.

Note that there are several approximate methods for calculation of reference (or potential) evapotranspiration, so-called radiation and temperature methods [7]. They do not reflect, however, the real soil moisture conditions and the influence of plant architecture on water uptake by the roots and on the transpiration. The effect of plant canopy can be taken into account by including the stomatal resistance as an additional term into balance equation, as it was done by Penning de Vries and van Laar [1]. But there were no relations enabling the connection of this resistance with the soil moisture, weather conditions and the architecture of the root system.

It is well-known that the transpiration is reduced by soil drying due to a decrease in plant water potential and stomata closing. This phenomenon serves as a basis in the models of water dynamics. The fact that the stomata become closed under submergence conditions is not familiar for everybody. In the model presented here stomatal resistance increases under both overdrying and overwetting conditions.

Let us consider the situation of soil drying first. Plant transpiration in accordance with Pennman method is described by the equation:

$$E_{\rm p} = \frac{s\,R + \sigma}{(s + \gamma^{*})\,\lambda} \qquad (1)$$

where s is the slope of the saturated pressure curve at air temperature in mbar K^{-1}, R is the radiation absorbed by plants, σ - the drying power of the air, and γ^{*} - the apparent psychrometric constant. The drying power of the air is defined as:

$$\sigma = \frac{(e_{\rm s} - e_{\rm a})\,\rho\,c_{\rm p}}{r_{\rm b}} \qquad (2)$$

where e_s is the saturated vapour pressure, e_a - the actual vapour pressure, $\rho\, c_p$ - the volumetric heat capacity of the air, r_b - the boundary resistance of the crop. The apparent psychrometric constant is defined by:

$$\gamma^* = \gamma \frac{r_b + r_{st}}{r_b} \quad (3)$$

where γ is 0.63 mbar $K^{-1}$and r_{st} is stomatal resistance of the leaves. All the variables entering into Eqs. (1-3), except for stomatal resistance, depend on the weather and can be easily computed. As for the last one, it is fully determined by water potential of the leaf, P_l, apart from the current weather conditions. Consequently, the plant transpiration, E_p, also depends on these variables:

$$E_p = E_p\,(P_l, \text{Weather conditions}).$$

On the other hand, water uptake by the roots uses both the soil and the root water potentials as its driving forces:

$$E_r\,(t) = \int_0^{h_r} \xi\, \omega(x,t)\, \left(P_r\,(t) - \psi(x,t)\right)\, dx \quad (4)$$

where ξ is hydraulic root conductivity, $\psi(x, t)$ - soil water potential, $\omega(x, t)$ - surface density of the root system, x - vertical coordinate directed downwards, h_r - the root depth.

Therefore, if the approximate equality

$$P_l \approx P_r \quad (5)$$

is valid, the condition of water balance of the plant yields:

$$E_p(t) = E_r(t) \quad (6)$$

and the last two equations can be used for the elimination of the unknown value of P_l from Eqs. (1-3). This situation is illustrated in Fig. 1, where an equilibrium P_l^* corresponds to relations (5,6). Similar method was developed by the authors for the calculation of the evaporation from the soil surface, E_s, [2]. The calculation of two components of evapotranspiration, E_p and E_s, provides the boundary condition and the sink function for the problem of the solution of differential equations of water movement in an unsaturated zone of the soil.

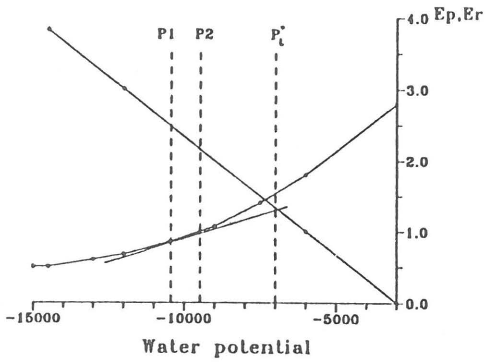

Fig. 1. Plant transpiration (Ep, cm/day) and water uptake by the roots (Er, cm/day) as a function of leaf water potential (P_l, cm).

Now let us consider the overmoistening case. Soil submergence can be affected by different causes - bogging up, field lowering in the landscape, ineffectiveness of the drainage system. We will discuss the case of a temporary submergence when such periods are alternated with optimal ones of periods of insufficient soil with moistening in the course of vegetation. It is well-known that under such conditions root aeration is reduced, the CO_2 concentration in the soil is increased, and the oxygen concentration is decreased. The plants transfer to the use of anaerobic sources of energy, and after they are exhausted, disintegration of cell structures begins and ATP content falls. Two processes are important from the simulation point of view: an increase in the hydraulic resistance on the boundary 'root - xylem' and a decrease in the water potential of the leaf, which leads to stomata closing. As a result, the photosynthesis rate is also reduced. These processes have to be reflected in the model.

Let us introduce a variable characterizing the degradation of vital plant features under the conditions of oxygen scarcity (*anoxia* or *hypoxia*). Let this variable be denoted as $Y(t)$ and be subordinated to the following differential equation:

$$dY/dt + \alpha Y = \alpha X \,. \qquad (7)$$

The input variable $X(t)$ equals zero under the conditions of sufficient oxygen content in the soil and equals unity be *hypoxia.* In other words:

$$X(t) = \begin{cases} 0 \text{ if } \theta(t) \le \theta_{FC} \\ 1 \text{ if } \theta(t) > \theta_{FC} \end{cases} \qquad (8)$$

where $\theta(t)$ is the soil moisture and θ_{FC} - the field capacity of the soil. Therefore, the variable $Y(t)$ gradually increases under submergence conditions reaching the unity by a long-term overmoistening, and is reduced if the soil moisture becomes equal or less than θ_{FC}.

Now we receive the possibility to describe in a natural way a hypoxic influence on water regime of the plants. Indeed, let us assume that water potential of the leaf is subordinated to the following equation:

$$P_l(t) = P_{opt} + Y(t)\left(P_{wp} - P_{opt}\right) \qquad (9)$$

where P_{opt} and P_{wp} are correspondingly the values of water potential by the field capacity and by the wilting point. The formula for the calculation of transpiration Eq. (1) remains valid, but the value of the leaf water potential corresponding to Eq. (9) must be substituted into it. Consequently, a gradual diminishing in the transpiration as well as a lowering in the photosynthesis rate will proceed during long-term submergence, which corresponds to well-known concepts on the exertion of the submergence stress to the plants. Note that the short-term overmoistening does not affect on a plant production process.

Now we can propose a relation connecting the current plant stress with the transpiration. Really, the transpiration reflects the soil water status from the point of view of water or oxygen availability to plants and of any deviations in soil moisture from its optimal content. The stress function based on account of transpiration under conditions of insufficient soil moisture was proposed by Shaw [3,4]. We propose to generalize this concept for both the deficit and excess of soil moisture. Let us consider the following equation:

$$IS(t) = \left(1 - E_p(t)/E_{po}(t)\right) \qquad (10)$$

where E_p is transpiration calculated according to Eq. (1), and E_{po} - a potential transpiration. The latter is computed following the same equation Eq. (1) but after substituting the value P_{opt} in it. As an inequality takes place:

$$P_l(t) \le P_{opt}$$

and the value of stomatal resistance increases monotonic by a decrease in P_l, the stress index remains within the limits:

$$0 \le IS(t) \le 1$$

and can be measured in relative units or in per cents. Note that $IS(t)$ equals unity during deep drought or long-term submergence and it is close to zero under comfortable conditions.

RESULTS AND DISCUSSION

The concepts stated above were realized in the summary model of plant cultivation for winter wheat and maize in the framework of AGROTOOL software package. The results of the simulation in comparison with experimental data are presented in Tables 1 and 2.

The first one relates to winter wheat grown in the Krasnodar region (Russia). The results of simulated and real yield levels for maize obtained at the experimental field Gorny Lozen (Bulgaria) are shown in Table 2. In all these cases submergence periods were alternated with drought ones either through precipitation excess or as a result of insufficiently correct irrigation. Figure 2 illustrates this statement. The regime of real irrigation is reflected in Fig. 2a. Figure 2b relates to the same vegetation season, but without irrigation. The difference between the two cases

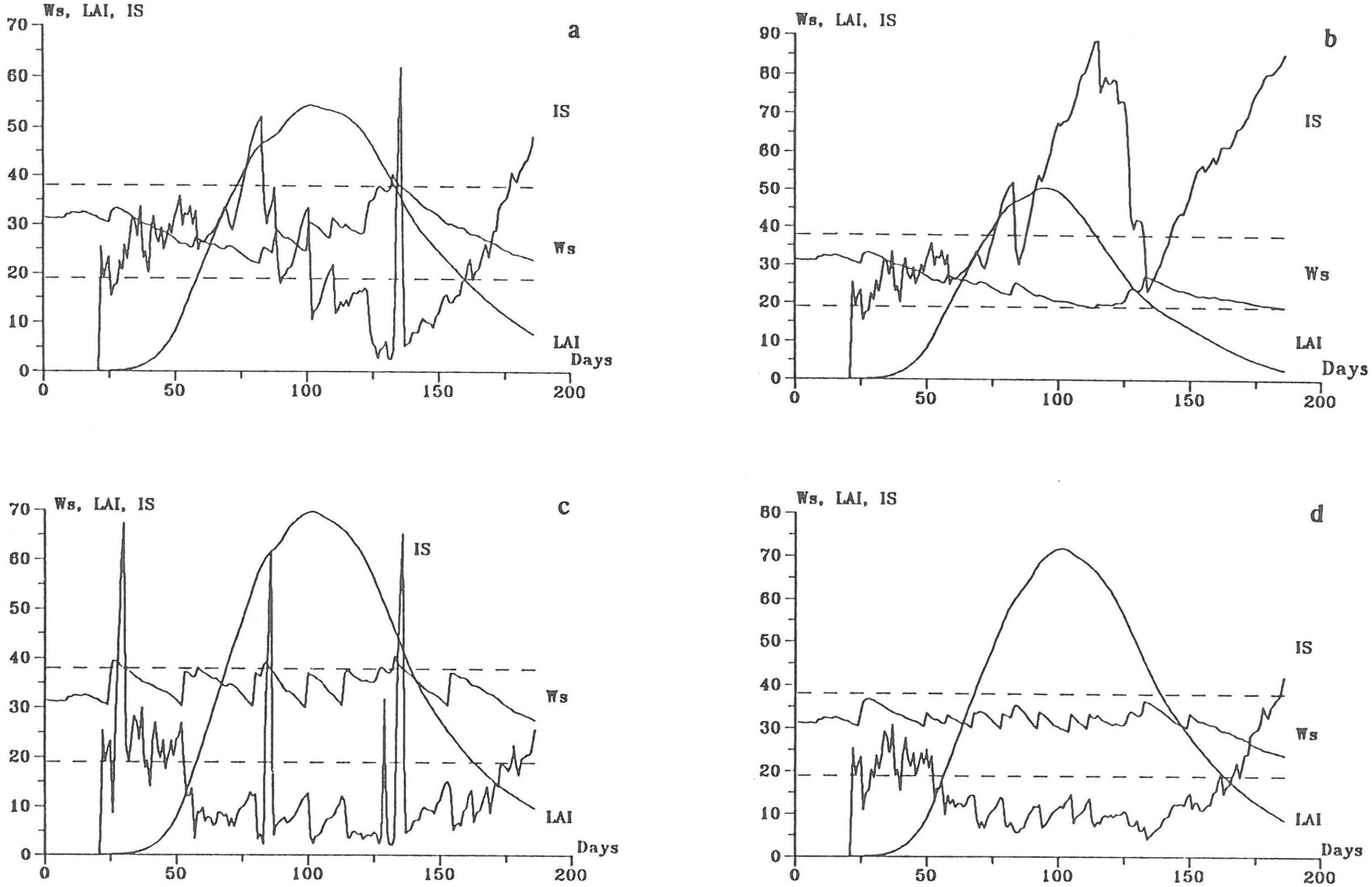

Fig. 2. Dynamics of soil water content (Ws, cm/m), leaf area index (LAIx10) and stress index (IS, %). Maize crop. a - real irrigation; b - without irrigation; c - optimal irrigation up to field capacity (FC); d - optimal irrigation up to 0.9 FC.

Table 1. Comparison of simulated and real yield levels for winter wheat

Vegetation season	Yield (t/ha)	
	simulated	real
1979/80	4.16	4.21
1980/81	5.12	4.50
1982/83	3.07	3.03
1983/84	3.46	3.04
1984/85	3.15	4.71

Table 2. Comparison of simulated and real yield levels for maize

Vegetation year	Yield (t/ha)	
	simulated	real
1980	10.5	9.7
1981	11.8	12.7
1982	11.4	11.9
1983	10.0	10.0
1984	11.7	12.0
1986	7.4	7.3

clarifies the deviations from optimal moisture conditions. Two cases of computer experiment with automatic irrigation are depicted in Fig. 2c and Fig. 2d. One can see that the amount of irrigating water with the aim to reach the field capacity (FC) temporary leads to water stresses resulting from possible precipitation after irrigation. It is better to restrict oneself in irrigating to 0.9 of FC (Fig. 2d).

CONCLUSIONS

The universal description of water stress index reflecting the deficiency of both water (under drought conditions) and oxygen (while submergence) is determined. The value of stress index bears the dynamic character in two cases. Really, the soil is drying slowly, of course. On the other hand, soil overmoistening can occur abruptly in the case of a large precipitation or irrigation. Nevertheless, an oxygen stress is slowly developed due to the initial storage of the internal plant energy.

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