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ENERGY LEVELS OF SOIL MOISTURE AND BIOPRODUCTIVITY

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A b s t r a c t. An agrophysical concept for estimating the crop water regime is offered. Two biophysical indices are introduced: for energy levels of the soil moisture and for their degree of appearance during the vegetation period. An energy level classification is developed that takes into account the biophysical relationship between the photosynthetic activity and the soil moisture potential, and the essential features of the potential changes of water in plants and soils. Equivalent energy levels were defined for natural crop water regimes during the whole vegetation period and its separate stages. A simple dependence of maize yield on the index of the energy levels was experimentally established when the soil moisture is the only limiting factor.

INTRODUCTION

The development of the modern science relating to the water regime of the Soil-Plant-Atmosphere (SPA) agrosystem follows two main directions. In the first one, the investigations have very limited scientific basis and their results are used for irrigation planning necessary for hydrotechnical construction. In the second one, the investigators are in search of complete scientific bases of the main processes which form a water regime of the agrosystem and their results are used for operative crop water management in a strict chronological sequence during the particular vegetation period.

For a long time, researchers in the first (planning) direction have tried to find a relationship between the total water consumption, evapotranspiration and the bioproductivity. They are using average data for periods covering many years. It was proved that the total water consumption during the whole period of vegetation is not proportional to the obtained yield [1,2]. Moreover, there is no simple dependence between the total irrigation quantity of water and the yield [6]. This complication is a fact which is explained by the variability of rainfall and watering distributions and other meteorological factors during different periods of vegetation. This variability exerts considerable influence on the crop yield formation.

In the second (biophysical) direction, scientists have accumulated a lot of knowledge about separate elements of the agrosystem and the separate processes forming its water regime [3,7-11]. In our opinion, the very important and urgent problems to be solved are the summing up of these attainments, the development of complete scientific bases for describing and estimating the water regime relative to the bioproductivity, and the creating of complex computer systems for operative control. The theoretical basis for crop water management is a scientific generalization of the recent achievements in this field [5]. The Complex Information System (CIS) uses this theoretical basis [4].

The present paper offers a scientific basis for estimating crop water regimes. It is a logical continuation of the above-mentioned theoretical basis.

THEORY

Agrophysical conception

Proceeding from the modern energetic notions of the process of the plant roots extracting water from the soil we developed the following concept.

The main effect of a water regime during the whole vegetation period on the bioproductivity is determined by a physical index L of the actual energy levels of soil moisture. This index is proportional to the lower limit ψ_m of the soil moisture potential ψ (absolute value) raised to the power of 1/2. A special schedule of plant-watering corresponds to each energy level L for every type of vegetation. Such a schedule should be received in chronological sequence during the particular vegetation period by means of the Complex Information System (CIS) for operative management and computer calculations [4,5].

We introduced a new physical index AD-degree of appearance of the energy level L during the vegetation - with the equation:

$$AD(L) = \frac{f_1}{n_1^0} n_1 + \frac{f_2}{n_2^0} + \frac{f_3}{n_3^0} n_3 \qquad (1)$$

where n_1, n_2 and n_3 are the numbers of the necessary rectifications of natural water regime (by means of irrigation, scheduled by the CIS) to keep this level L during the extreme-critical, critical and important stages of the crop growth, respectively; n_1^0, n_2^0 and n_3^0 are the maximum numbers of th necessary rectifications (to keep the same L during the mentioned stages), received by means of the CIS when all rainfall is eliminated; f_1, f_2 and f_3 are the weighting factors for these stages in relation to the soil moisture. The index AD takes into account the number of cases when the soil moisture potential is lowered to the admissible minimum values, corresponding to the chosen energy level L. Every such case is identified by the date and stage of the crop growth in the CIS.

We also introduced equivalent energy levels L_e for a quantitative estimation of crop water regimes of the SPA agrosystem under irrigated and nonirrigated conditions by means of the equation:

$$L_e = f_1 L_{ec} + f_2 L_c + f_3 L_i \qquad (2)$$

where L_{ec}, L_c and L_i are the soil moisture energy levels established during the three specified stages of crop growth. These levels correspond to the minimum value of soil moisture potential during each stage and can be determined experimentally by measuring the soil moisture and using the drying water retention curve.

The soil moisture potential ψ as a function of the volumetric soil moisture θ can be calculated with good approximation using Gardner's equation:

$$\psi(\theta) = A\,\theta^{-B} \qquad (3)$$

and our coefficients:

$$A = 1\,560\,\theta_w^{B} \qquad (4)$$

$$B = \frac{\ln \psi_w - \ln \psi_f}{\ln \theta_f - \ln \theta_w}\,. \qquad (5)$$

Equations (3), (4) and (5) can be used if we know the soil moisture values θ_w and θ_f at the potentials ψ_w = -1 560 J/kg and ψ_f = -20 J/kg for every genetic horizon of the soil profile. Using the values of the moisture potential minimum obtained during those three stages of vegetation and the classification of energy levels suggested in Table 1, we can estimate equivalent energy level L_e for the whole period of vegetation.

Classification of energy levels

The classification given in Table 1 is developed as a result of generalizing the following relationships: photosynthetic intensity as a function of the soil moisture potential, moisture potential as a function of the volumetric soil moisture, crop growth as a function

Table 1. Classification of energy levels L based on the lower limits ψ_m of soil moisture potential during extreme-critical (e-c), critical (c) and important (i) stages of plant growth

Class No.	Class name and range of lower limits ψ_m	L	ψ_m (J/kg)	
			(e-c)	(c & i)
I	Biological optimum (-50, -10)	1	-20	-20
		2	-20	-40
		3	-40	-40
		4	-40	-50
		5	-50	-50
II	Middle levels (-100, -50)	6	-50	-60
		7	-60	-60
		8	-60	-80
		9	-80	-80
		10	-100	-100
III	Slightly lowered levels (-200, -100)	11	-120	-120
		12	-130	-150
		13	-160	-160
		14	-160	-200
		15	-200	-200
IV	Moderately lowered levels (-400, -200)	16	-230	-230
		17	-240	-270
		18	-300	-300
		19	-320	-350
		20	-400	-400
V	Strongly lowered levels (-600, -400)	21	-430	-450
		22	-460	-480
		23	-520	-520
		24	-540	-580
		25	-600	-600
VI	Transitionally low levels (-900, -600)	26	-650	-650
		27	-680	-720
		28	-770	-770
		29	-820	-860
		30	-900	-900
VII	Medially low levels (-1 300, -900)	31	-960	-960
		32	-1 000	-1 050
		33	-1 100	-1 100
		34	-1 100	-1 200
		35	-1 200	-1 250
VIII	Very low levels (-1 600, -1 300)	36	-1 300	-1 300
		37	-1 370	-1 370
		38	-1 450	-1 450
		39	-1 520	-1 520
		40	-1 600	-1 600
IX	Extreme low levels (below -1 600)	41	-1 700	
		42	-2 000	
		43	-2 500	
		44	-5 000	
		45	-10 000	

of the soil moisture minimum during vegetation. A great deal of experimental data were used for the limits of soil moisture available for plants, and for the influence of soil physical properties on the availability of soil moisture.

Index L, which has the physical dimension $J^{1/2}/kg^{1/2}$, is the basic parameter of each energy level of soil moisture in this classification and it can be determined both for the whole vegetation and for the separate stages of crop growth. The dependence between L and ψ_m in the interval of soil moisture available for plants is chosen in such a way as to fix the number of energy levels, and so that index L should serve as a natural number for the same levels.

In the interval of soil moisture available for plants, i.e., by L from 1 to 40, the statistical analysis of the values of L and ψ_m proved a high quadratic correlation. The coefficient of correlation was equal to 0.9994. We had to introduce five energy levels out of this interval in order to take into account the plant's ability for adaptation under dry conditions. The soil moisture energy levels were separated to 9 classes.

The first class - class of the biological optimum - is specified by an allowed value of photosynthetic intensity reduction up to 12 % of the maximum intensity. The soil moisture potential is higher or equal to -50 J/kg during the active vegetation. The maximum reduction of photosynthetic intensity for the second class - class of the middle levels - is 35%, and the lower limit of moisture potential varies from -100 to -50 J/kg. The third class is a class of the slightly lowered levels. The lower limit of potential varies from -200 to -100 J/kg. The photosynthesis reduction reaches 90 % only because of the soil moisture potential desease.

The fourth and the fifth classes include moderately and strongly lowered energy levels. Within the fourth class the photosynthetic intensity can be some percentage of the maximum, in the fifth class photosynthesis can be interrupted during some intervals of the period of vegetation. The lower limit of potential varies from -400 to -200 J/kg in the fourth and from -600 to -400 J/kg in the fifth class.

The sixth, the seventh and eighth classes include transitionally, medially and very low energy levels of soil moisture, respectively. Within these classes the lower limit of potential can be from -600 to -1 600 J/kg, i.e., up to the full consumption of moisture available for plants. In these limits of potential the utilization of soil moisture by plants is more difficult than the moisture which corresponds to the first, second and third classes. In this respect the fourth and fifth classes are transitional. Photosynthesis stops for a long time during the vegetation period, and after watering or rain it partially recuperates. The crop yield lowers up to zero as a function of the energy level of soil moisture reached in the root zone.

The ninth class includes extreme low energy levels of soil moisture at which the potential is allowed to reach values under -1 600 J/kg. Because of the absence of moisture available to plants during some intervals of time those crops that were well-developed before those intervals may give very low and bad yields or wither up.

Experimental application of the concept

The crop yield formation is a complex function which depends on the plant growth during the whole period of vegetation. The environmental factors and the specific demands of the crop affect this plant growth. So, to apply the concept we carried out multifactor field experiments with maize in north-western Bulgaria during the period 1982-1987. Using the Complex Information System CIS for operative management we realized some soil moisture energy levels with L equal to 5, 10, 15 and 16 under field conditions. The natural water regimes were estimated by an equivalent energy level L_e as follows: 16 for 1982, 20 for 1983, 25 for 1984, 32 for 1985, 22 for 1986 and 26 for 1987. For all experimental variants of the yield formation, appropriate mineral fertilizing is carried out so that plant nutrition is not a limiting factor during the vegetation period.

The results of the field experiments showed a simple dependence of the yield Y, t/ha, on the energy level index L:

$$Y = 19.214 - 0.516\,L \quad (6)$$

Statistical analysis of the experimental data proved Eq. (6) - with a high coefficient of correlation - to be equal to 0.973. The standard deviation is ± 0.5 t/ha.

In Fig. 1 the experimental data for the maize yield at standard moisture level are given as a function of L. In the prevalent part of the interval of soil moisture available for plants, the yield diminished linearly with the increase of L, i.e., with the decrease of the lower limit of soil moisture potential during the different vegetation periods. In the domains of the biological optimum (L changes from 1 to 5) and of the low levels with L more than 30, we expect some complications because of adaptive and other biological peculiarities, and the possibility of other limiting factors being introduced such as poor aeration in the root zone, etc. In these extreme domains the energy levels are not important for practical purposes. Their realization is connected with many difficulties and needs special meteorological conditions.

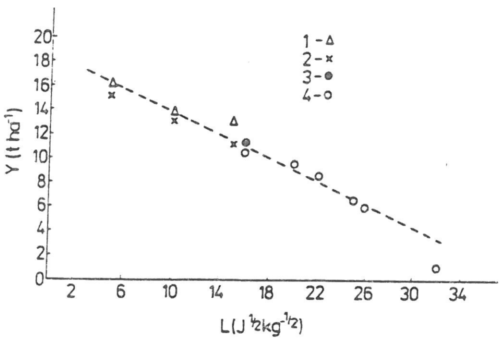

Fig. 1. Experimental data of maize yield Y, versus soil moisture energy levels L. Each L is realized by a special irrigation schedule, determined by the CIS and computer in chronological sequence during every period of vegetation under consideration. Explanations: 1 - crop yield received at the given energy levels which were maintained by furrow irrigation in 1986, 2 - crop yield received at the same levels maintained by furrow irrigation in 1987, 3 - stable crop yield about 10 t/ha, received at the level of L=16 $J^{1/2}kg^{-1/2}$ which was maintained by sprinkling irrigation during the period 1982-1985, 4 - crop yield received at the equivalent energy levels corresponding to natural water regimes during the period 1982-1987, i.e., with no irrigations.

CONCLUSIONS

The agrophysical concept presented and the indices introduced correctly reflect the energetic nature of soil moisture extracted by plants. The concept explains the effects of soil moisture on the yield formation when other factors are limiting plant growth. Our classification of soil moisture energy levels together with equations can be utilized to assess crop water regimes, created under irrigated and nonirrigated conditions. The present theory is a necessary component of irrigation control by means of the Complex Information System and computer. Eq. (6) enables the maize yield to be calculated in the region under consideration. Obviously this equation should be adapted for every crop and geographic region with different climatic (solar radiation being of paramount significance) conditions and specific limiting factors.

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