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THE RELATION OF ACTUAL TO POTENTIAL EVAPOTRANSPIRATION AS AN INDICATOR OF PLANT WATER STRESS FOR MEADOW PLANT COVER

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Summary. In this paper a scheme of determination of actual E_a to potential E_p evapotranspiration relation, enabling the calculation of crop water stress index *CWSI* is presented. In the lysimetric study the actual evapotranspiration was calculated from the energy balance equation in which radiation temperature of plant cover measured with the use of thermographic device is a component of sensible heat flux equation expressing the transport of heat energy from evaporating surface to the atmosphere. Penman-Montheith method of potential evapotranspiration calculation was used as fitting the best the daily courses of actual evapotranspiration for the conditions of unlimited soil water availability for rooting system. It was stated that the relation of actual to potential evapotranspiration changes follow the changes of plant water potential. The obtained results confirmed the utility of the method using plant cover radiation temperature measurements for stating the moment of oncoming or persisting plant water stress and can be helpful in the attempt of evaluation with high accuracy the evapotranspiration of large agriculturally used areas.

Keywords: crop water stress, evapotranspiration, thermography.

INTRODUCTION

The knowledge of evapotranspiration rate is necessary for evaluation of physiological processes intensity as well as for evaluation of water resources utilisation. The actual evapotranspiration rate of plant cover mainly depends on meteorological conditions and soil water availability for the rooting system. Therefore the accuracy of its evaluation depends on taking into account many physical parameters describing soil-plant atmosphere system. Many physical and physical-phenomenological models exist for determination of actual evapotranspiration [3, 9].

The potential evapotranspiration, being strongly dependent on meteorological conditions, cannot be directly used for evaluation of plant water stress which is mainly determined by soil water conditions. Many efforts were undertaken to find an indicator of plant water stress basing on evapotranspiration rate evaluation. The indicator basing on the relation between actual and potential evapotranspiration seems to be the most promising [5, 6].

The application of radiation temperature measurement of plant cover increases the accuracy of actual evapotranspiration evaluation because plant itself is the best sensor of the physiological processes taking place in it [2]. Evapotranspiration as an energy consuming process causes the decrease of plant temperature. The investigations confirmed the possibility of the application of thermography method for determination of the impact of soil water availability for the rooting system on actual evapotranspiration rate and therefore on leaf temperature forming. The hypothesis that the equations for actual evapotranspiration evaluation, including radiation temperature as a parameter, give the best accuracy, was verified experimentally. The thermography technique proved to be a good tool in the investigations of quantitative relation between evapotranspiration rate and the set of agroclimatic factors [2, 7, 8].

The aim of this paper is presentation of the method of crop water stress determination using the measurement of plant cover radiation temperature, basing on the relation of actual to potential evapotranspiration.

THEORY OF CROP WATER STRESS DETERMINATION

The energy balance equation describes the process of energy exchange at the evaporating surface (e.g. crop surface). The most frequently used form of this equation is as follows:

$$LE + H + R_n + G = 0 \qquad (1)$$

where: LE – the latent heat flux [$W \cdot m^{-2}$] (energetic equivalent of the evapotranspiration flux); L – the latent heat of vaporisation of water per unit mass ($L = 2.45 \cdot 10^6$ $J \cdot kg^{-1}$); E – evapotranspiration flux [$kg \cdot m^{-2} \cdot s^{-1}$]; H – the sensible heat flux [$W \cdot m^{-2}$]; R_n – the net radiation flux [$W \cdot m^{-2}$]; G – the heat flux into the soil [$W \cdot m^{-2}$].

In this equation fluxes towards the crop surface are given the positive value and the fluxes out of the surface are given the negative value.

Heat and energy transport in soil-plant-atmosphere system can be described using resistance model built as an analogue of electric circuit. The transport equations for sensible heat H and latent heat $L \cdot E$ in this case can be expressed as:

$$H = -\rho \cdot c_p \frac{T_c - T_a}{r_{ah}} \tag{2}$$

$$LE = -\frac{\rho \cdot c_p}{\gamma} \frac{e_c^* - e_a}{r_{av} + r_c} \tag{3}$$

where: T_c – crop surface temperature [K]; T_a – air temperature [K] measured at reference height z_a; e_c^* – saturated vapour pressure [Pa] at the apparent crop temperature T_c; e_a – water vapour pressure of the air [Pa] measured at reference level z_a; r_{ah} , r_{av} – aerodynamic resistance respectively for transport of heat and water vapour [$s \cdot m^{-1}$]; r_c – resistance of the crop [$s \cdot m^{-1}$]; ρ – density of air [$kg \cdot m^{-3}$]; γ – psychrometric constant; c_p – air specific heat [$J \cdot kg^{-1} \cdot K^{-1}$].

Aerodynamic resistance for heat transport r_{ah} is a function of wind velocity, stability of the atmosphere over the plant cover and the roughness of the surface. As a good approximation it can be assumed that $r_{ah} = r_{av} = r_a$ (turbulent diffusion resistance for sheat and water vapour transport). Combining equations (1), (2) and (3) we obtain the relation between actual value of radiation temperature of evaporating crop surface and agrometeorological parameters in the atmospheric boundary layer and soil:

$$T_c = T_a + \frac{r_a(R_n - G)}{\rho c_p} \cdot \frac{\gamma\left(1 + \frac{r_c}{r_a}\right)}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} - \frac{e_a^* - e_a}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)}. \tag{4}$$

It results from this equation that the difference between crop surface temperature and air temperature is linearly dependent on the difference between water vapour pressure at plant canopy level and water vapour pressure in the atmosphere. This relation was used by Jackson et al. [5, 6]. They created crop water stress index (*CWSI*). This index bases on relation of the actual evapotranspiration to potential evapotranspiration and is expressed as:

$$CWSI = 1 - \frac{E_a}{E_p} = \frac{\gamma\left(1 + \frac{r_c}{r_a}\right) - \gamma\left(1 + \frac{r_{cp}}{r_a}\right)}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \tag{5}$$

where: E_a – actual evapotranspiration flux [kg · m^{-2} · s^{-1}]; E_p – potential evapotranspiration flux [kg · m^{-2} · s^{-1}]; r_{cp} – the canopy resistance at potential evapotranspiration [s · m^{-1}]; the other symbols as in previous equation.

METHODS

For calculation of hourly and daily values of actual evapotranspiration the heat balance method was used in which latent heat flux is treated as an unknown in eq. 1, sensible heat flux was calculated from eq. 2 on the base crop surface radiation temperature measurement and the other components (R_n and G) were determined on the base of standard meteorological measurements. On the base of radiation temperature differences in lysimeters and air temperature, the stability conditions in the boundary layer of atmosphere were determined. Turbulent diffusion resistance r_a was calculated using equations of semi-empirical theory of turbulence [4, 9].

The chosen method of actual evapotranspiration calculation requires relatively small number of input parameters, available from standard meteorological stations except from radiation temperature of crop cover. This parameter can be obtained even for large areas from remote sensing materials from different levels, being more and more easily available these days.

In this study Penman method was used for potential evapotranspiration calculation. Furthermore this method enables to decrease the number of input data by incorporating into the equations experimentally verified relations between the physical quantities included into the models. From among different modifications of Penman equation of potential evapotranspiration calculation [1], the Penman-Monteith method was chosen, giving the best correlation with actual evapotranspiration values for the conditions of unlimited soil water availability for rooting system.

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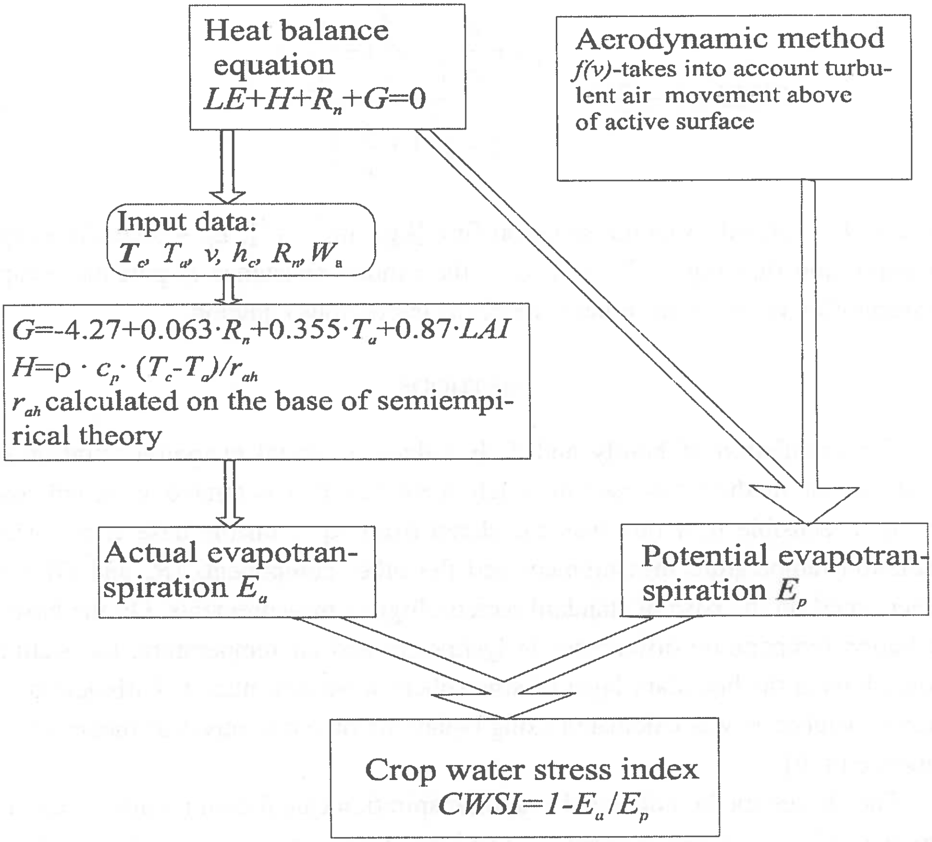

Fig. 1. A scheme of determination of actual evapotranspiration E_a, potential evapotranspiration E_p, and crop water stress index *CWSI*.

The physical quantities in Fig. 1 are as follows: *LE* – latent heat flux, *H* – sensible heat flux, R_n – net radiation, *G* – heat flux in the soil, *Tc* – crop temperature, T_a – air temperature, *v* – wind speed, h_c – crop height, W_a – relative air humidity, r_{ah} – aerodynamic resistance for heat transport, ρ – air density, c_p – specific heat of the air, *LAI* – leaf area index, *f(v)* – a function of wind speed.

The calculated actual and potential evapotranspiration values led to calculation of the crop water stress levels of the studied plant cover by utilisation of the Crop Water Stress Index (*CWSI*).

EXPERIMENT DESCRIPTION

The experiment was performed in lysimetric station of the Institute for Land Reclamation and Grassland Farming in Sosnowica (51°31'30"N, 23°04'48"E). The station is situated in the central part of Wieprz-Krzna Canal district, 164 m above sea level. The object of the study was natural grass cover growing in lysimeters of the area 1700 cm^2 and height 120 cm. (Lysimeters with different ground water levels of sandy and peat soil). In initial stage of the experiment the optimal water level of 60 cm was kept in all the lysimeters. Soil water content in lysimeters was differentiated. The pairs of lysimeters were created and in each pair there was one lysimeter with gravitational water completely carried away and the other with soil water level representing the comfort water conditions for plants.

Thermal images of plant cover in lysimeters were taken with AGEMA 880 LWB. One minute sequences were taken every hour during daily hours and every two hour at night. The measurements of radiation temperature of each pair of lysimeters were done from the distance of 4.3 m and height of 2.2 m with the angle 60° between optical axis of the camera and the perpendicular. The whole day registration of meteorological data was performed with the use of automatic data acquisition system elaborated in IA PAS Lublin. The subsystem referring to the soil was composed of TDR (Time Domain Reflectometry) water content measuring device and thermoelectric sensors of soil temperature. The subsystem referring to the atmosphere was composed of thermoelectric sensors of air temperature, anemometers, psychrometers and sensors for direct and reflected short and long wave solar radiation. Water potential in plants was measured with Wescor device using dew point method.

RESULTS

Basing on eq. 4 the upper limit of crop-air temperature difference was found representing the complete restrain of evapotranspiration ($r_c \rightarrow \infty$) and the lower limit which corresponds to the case of wet plants acting as free water surface ($r_c = 0$) (Fig. 2). The regression line for well watered plants is close to the lower limit line and the regression line for stressed plants is close to the upper limit. Upper and lower limits in Fig. 2 were calculated for net radiation higher than 500 $W \cdot m^{-2}$, turbulent aerodynamic resistance 90 $s \cdot m^{-1}$ for stressed plant cover and 68 $s \cdot m^{-1}$ for plants in comfortable water conditions and air temperature 30°C.

High dispersion of measuring data for the lysimeters with stress water conditions was noticed (R^2 = 0,10) comparing with the data for the lysimeters with comfort soil water conditions (R^2 = 0.75).

Hourly values of *CWSI* and crop temperature are presented in Fig. 3 for plant cover in lysimeters of one pair. *CWSI* was calculated from equation 5. Potential evapotranspiration was calculated from Penman-Monteith formula and actual evapotranspiration using heat balance method.

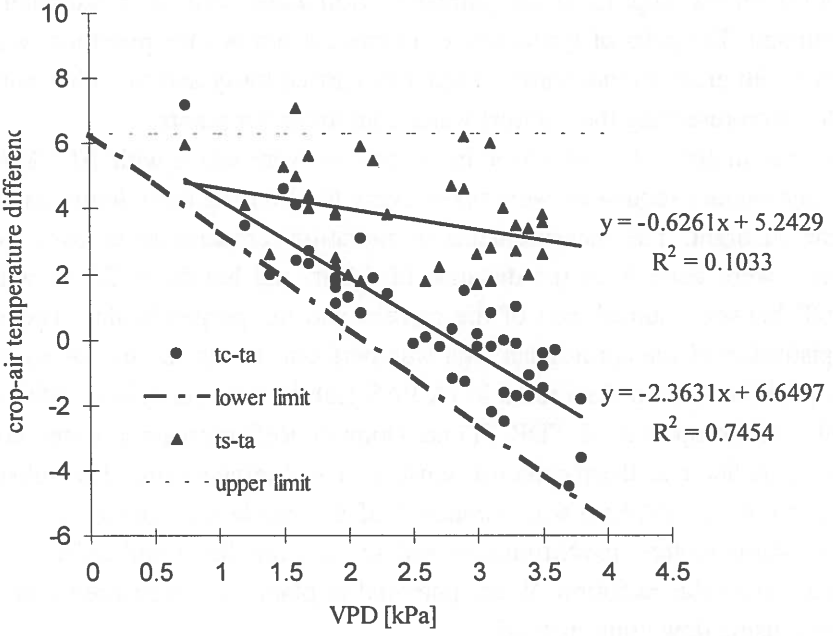

Fig. 2. The relation between crop-air temperature difference for stressed ts-ta and non-stressed tc-ta plants and vapour pressure deficit.

During daily hours the differences of crop cover temperature and *CWSI* values between stressed and non-stressed plants were observed. In Fig. 3 there are two values of *CWSI* above 1 what is not accountable according to the definition of this stress index. This inconsistency can be explained on the basis of the variability in the base line itself. The uncertainty in estimating the upper temperature limit is probably the main reason of this situation.

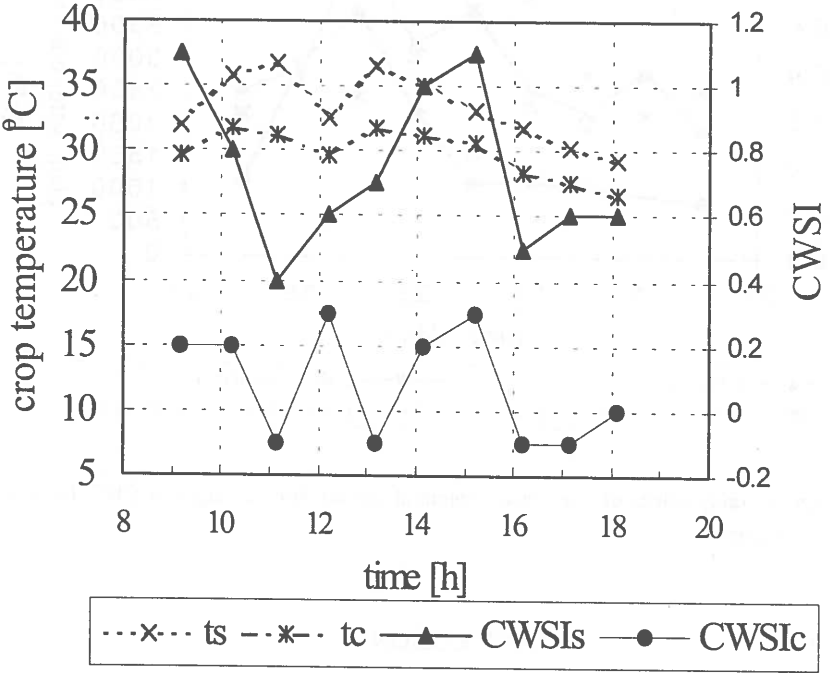

Fig. 3. Daily courses of *CWSI* for water stressed ($CWSI_s$) and non-stressed ($CWSI_c$) plants against a background of crop temperature courses: (t_s – stressed plants, t_c – comfort water conditions).

Evapotranspiration intensity is mainly determined by availability of soil water for plants. High differences of water potential exist in soil-plant-atmosphere system. Under high atmospheric evaporative demand (high water pressure deficit) the differences of soil water potential lead to considerable differences of plant water potential and evapotranspiration rate.

In Fig. 4 high differences of plant water potential are observed for succeeding days between the lysimeters of one pair. Simultaneously the high differences of *CWSI* values are noticed.

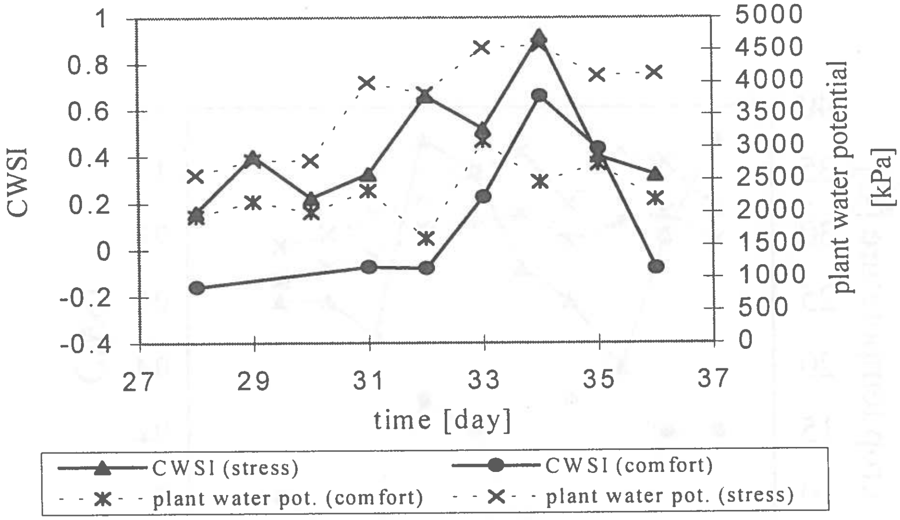

Fig. 4. Changes of daily values of plant water potential and resulting changes of *CWSI* for stressed and non-stressed plants.

CONCLUSIONS

Infrared thermography is a good tool in the studies of plant water stress and evapotranspiration. It enables automatic averaging of the thermal characteristics of a great number of individual plants from a large area and at the same time as opposed to the infrared thermometers it gives the possibility of selecting in the image and eliminating thermal signals coming from disturbing objects (eg. shown through soil).

Plant cover temperature in connection with standard meteorological data when incorporated into the heat balance equation makes it possible to determine hourly and daily values of actual evapotranspiration.

The combination of actual and potential evapotranspiration values leads to creation of the index of plant water stress *CWSI* which is sensitive to the atmospheric-evaporative demand and plant water potential.

For plants being in conditions of water comfort *CWSI* index does not exceed 0.3 while for the condition of limited soil water availability for plants it changes between 0.3 and 1.0.

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STOSUNEK EVAPOTRANSPIRACJI RZECZYWISTEJ DO POTENCJALNEJ JAKO WSKAŹNIK STRESU WODNEGO ROŚLINNOŚCI ŁĄKOWEJ

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S t r e s z c z e n i e. W pracy przedstawiono schemat określania stosunku ewapotranspiracji rzeczywistej E_a do potencjalnej E_p umożliwiającego wyznaczanie wskaźnika stresu wodnego roślin CWSI. W doświadczeniu lizymetrycznym określano ewapotranspirację rzeczywistą z równania bilansu cieplnego, w którym temperatura powierzchni roślin mierzona urządzeniem termograficznym jest składnikiem strumienia ciepła jawnego, wyrażającego transport energii cieplnej od parującej powierzchni do atmosfery. Wykorzystano metodę Penmana-Montheitha obliczania ewapotranspiracji potencjalnej. Dzienne przebiegi ewapotranspiracji potencjalnej uzyskane tą metodą były najbardziej zbliżone do dziennych przebiegów ewapotranspiracji rzeczywistej dla warunków nieograniczonej dostępności wody glebowej dla systemu korzeniowego. Stwierdzono, że trend zmian stosunku ewapotranspiracji rzeczywistej do potencjalnej był zbliżony do zmian potencjału wody w roślinach. Otrzymane wyniki potwierdziły przydatność metody wykorzystującej pomiar temperatury pokrywy roślinnej metodą termografii do określania zbliżającego się lub trwającego stresu wodnego roślin oraz ewapotranspiracji dużych obszarów użytkowanych rolniczo.

Słowa kluczowe: stres wodny roślin, ewapotranspiracja, termografia.

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